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Optimization of SBR system for enhanced biological phosphorus and nitrogen removal

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ABSTRACT

Aims: The aim of this study was the optimization of the SBR system for enhanced biological phosphorus and nitrogen removal.
Materials And Methods: A lab-scale SBR consisting filling, pre-anoxic, anerobic, anoxic, aerobic, settling, decanting, and idle phases was proposed for simultaneous enhanced biological phosphorus and nitrogen removal (SEBPNR) from wastewater. Synthetic wastewater was used in this research. Glucose was used as a carbon source. The SBR was seeded with sludge from a local municipal wastewater treatment plant.
Results: The results indicates that the lab-scale SBR was capable to remove soluble phosphorus (SP), SCOD, TCOD, and ammonia, with efficiencies of around 92%, 95%, 80%, and 85%, respectively. Optimized lab-scale SBR operational condition for SEBPNR consists of a fill (15 min), pre-anoxic (30 min), anerobic (90 min), 1st aerobic (210 min), 2nd anoxic (55 min), 2nd aerobic (10 min), settling (90 min), decant (10 min), and idle (10 min) phases.
Conclusion: This study concludes that effective biological removal of phosphorus and nitrogen from wastewater using SBR occurs in sufficient HRT in the anaerobic and aerobic stages, adequate COD/TP ratios (up to 35). This system is suitable for high removal of P and N in both municipal and industrial wastewater.

Key words: Denitrification, enhanced biological phosphorus removal (EBPR), nitrification, sequencing batch reactor (SBR), wastewater

INTRODUCTION

In the future, wastewater treatment facilities need to be adapted to make wastewater management more affordable and sustainable.[1] Management of nutrients in the effluent is a key issue in wastewater treatment systems, because some of them (such as phosphorus and nitrogen) are scarce resources.[2] Biological denitrification is a reliable method for nitrogen removal from wastewater. Heterotrophic bacteria use the available carbon source.[3] Since nitrified liquor is usually deficient in organic carbon and the low carbon source level limits the biological denitrification process, sufficient organic carbon sources must be provided for proper denitrification. In addition, for proper biological phosphorus removal, an easily biodegradable carbon source is needed at the P release stage (anerobic phase).[4]

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Biological phosphorus removal from wastewater is based on

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the activity of phosphorus-accumulating organisms (PAOs). In the anerobic phase, PAOs take up readily biodegradable organic carbon substrates and store them as poly-hydroxy-alkanoates (PHAs).[5] The energy to this anerobic process is derived from the hydrolysis of intracelluar polyphosphate and the glycolysis of glycogen followed by the release of orthophosphate to the bulk liquid.[6,7]

A sequencing batch reactor (SBR), the so-called fill and draw reactor, separates operating conditions timely in a single reactor. Different from continuous-flow-activated sludge systems, various biological reactions are switchable in the same reactor.[8] In the SBR, clarifiers and flow-equalization tanks are unnecessary, and thus costs of facilities and operation management are much lower than those of continuous flow activated sludge systems.[9] Moreover, the SBR has benefits in that it is easy to change operating conditions, such as cycle times and flow rates.[10,11]

Eutrophication of water caused by nitrogen and phosphorus has become a focus of concern recently, and development of remediation technology has become important.[12] Nitrogen can be removed as a final product of nitrogen gas by the combined reactions of aerobic nitrifiers and anerobic denitrifiers, while phosphorus can only be removed by its uptake into a biomass which can be discharged from the system as a surplus sludge.[13]

Removal of nutrient from wastewater prior to disposal is being required more frequently. As both phosphorus and nitrogen can impact receiving water quality, especially in producing eutrophication phenomena, the discharge of one and both of these constituents have to be controlled.[14] This study aimed to establish an approach to removing phosphorus and nitrogen in an optimized SBR system simultaneously. In this work, the technical feasibility of simultaneous phosphorus and nitrogen removal was investigated in a SBR system by enhancing anoxic phosphate uptake. For this, an anoxic phase was introduced into the first stage of anerobic phase of anaerobic–aerobic-anoxic SBR. In this case, nitrite could serve as an electron acceptor for anoxic phosphate uptake and can attribute phosphate releasing in the following anaerobic phase.

MATERIALS AND METHODS

SBR system

The SBR system consists of five sequencing stages including fill, react, settle, draw, and idle that are controlled by time to achieve the objectives of operation. The SBR process includes anerobic, anoxic, and aerobic reactions, followed by the settling stage that is carried out in a single-stage tank.

In this research, for installation of the SBR system in the laboratory scale, a glass container with total capacity of 3 L was used. The aeration of system was carried out by diffused aeration system and mixing of wastewater was done by electrical magnet. The working volume of the SBR system was 2 L.

Synthetic wastewater and sludge

Synthetic wastewater was used in this research. Glucose was used as a carbon source, and phosphate in the wastewater was simulated with potassium dihydrogen phosphate (KDP). Synthetic wastewater of the following compositions was used as the feeding solution in this research (per liter): 200-400 mg glucose ($C_6H_{12}O_6$), 80-160 mg ammonium chloride (NH_4Cl), 30-40 mg dihydrogen phosphate (KH_2PO_4), 20 mg magnesium sulfate ($MgSO_4$), 40 mg sodium hydrogen carbonate ($CHNaO_3$), 20 mg sodium chloride (NaCl), 500 mg sodium acetate (CH_3COONa, $3H_2O$). The pH of the solution was adjusted to 6-7.5 using NaOH 1N solution.[13,15,16] The activated sludge obtained from an aerobic basin of a local municipal wastewater treatment plant where nutrients were efficiently removed was used as the inoculating sludge for the SBR operation. The amount of used sludge was around of 10-15% of wastewater volume with general compositions of MLSS, MLVSS, and bacterial count equal to approximately 3000 mg/L, 2400 mg/L, and 10^{10} MPN/100 mL, respectively.

Batch experiments

A schematic of initial operational stages for the lab-scale SBR with different phases was depicted in Figure 1. The SBR system was operated with 15 running sequencing operational cycles at a cycle time of 420-560 min (7-9.3 h), in nine phases consisting of a 10-15 min filling phase, a 5-45 min first anoxic phase, a 90-180 min anerobic phase, a 60-210 min first aerobic phase, a 45-75 min second anoxic phase, a 0-30 min second aerobic phase, a 90 min settling phase, a 10 min decant phase, and a 10-20 min idle phase. In this study, in order to obtain appropriate removal of phosphorus (P) and nitrogen (N), five main metabolic stages with variable operational times were considered, including 1st anoxic, anerobic, 1st aerobic, 2nd anoxic, and 2nd aerobic. Stages of filling, settling, decanting, and idle were operated with constant times. Details of different operational conditions for nine phases with 15 stages of lab-scale SBR are presented in Table 1. Optimum operational conditions of the SBR system is shown in Figure 2.

As shown in Figure 1, the SBR system in this study consisting different process phases include a short-time 1st anoxic for the removal of interfering nitrate ion and consumption of molecular oxygen that probably exist in the raw wastewater, an anerobic for microbial P release stage, an aerobic stage for nitrification and P uptake, a 2nd main anoxic stage for denitrification, and a 2nd aerobic to convert the NO_3^--N and NO_2^--N to N_2 gas and contribute in proper sludge settling.

In order to biomass production to bio-removal of phosphorus and nitrogen from synthetic wastewater, there was need for microbial populations. According to Metcalf and

Table 1: Different operational times of lab-scale SBR system

Steps	SBR operational conditions	Stages 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		Hydraulic Retention Time (min.)														
1	Fill	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
2	Anoxic	5	5	10	10	15	15	20	20	25	25	30	30	35	40	45
3	Anaerobic	125	90	180	150	180	150	125	120	100	90	90	100	90	90	90
4	Aerobic	60	120	60	120	100	120	150	150	180	200	210	210	210	210	210
5	Anoxic	75	60	55	30	30	45	45	60	60	60	55	45	60	60	60
6	Aerobic	30	30	10	15	10	15	15	15	10	10	10	20	20	25	30
7	Settle	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90
8	Decant	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
9	Idle	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Sum of steps of 2-6		295	305	315	325	335	345	355	365	375	385	395	405	415	425	435
Total cycle time		420	430	440	450	460	470	480	490	500	510	520	530	540	550	560

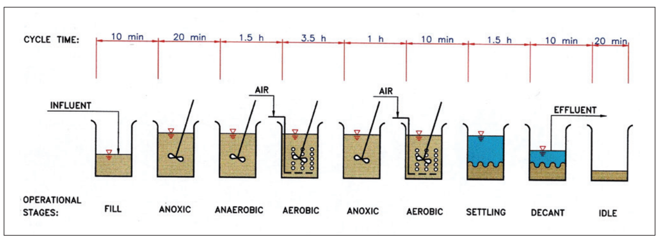

Figure 1: Schematic of initial lab-scale SBR operational condition for biological phosphorus and nitrogen removal

Eddy, the required MLSS (mixed liquor suspended solids) concentration for the SBR process is in the range of 1500-4000 mg/L.[7] To increase the MLSS concentrations and microbial growth rates in the synthetic wastewater, 100-200 mL of municipal wastewater, collected from aeration basin, was added to the mixture. The MLSS concentration was measured every day and about 80% of mixture was decanted and new prepared synthetic wastewater was substituted which the volume of solution was reached to 10 L. The pH was adjusted in the range of 7-7.5. Samples were collected for microbial observation every 3 days. After 1 month, the MLSS concentration reached to about 3000 mg/L with a wide range of different types of activated sludge micro-organisms (i.e., bacteria, ciliate, and rotifers). Then, the actual operation of the SBR system was started with different compositions of synthetic wastewater. Under different influent synthetic wastewater compositions, the pilot plant was operated with different hydraulic retention times in order to achieve proper removal of phosphorus and nitrogen.

The COD concentration in the feed for different operational conditions of SBR was about 220 ± 10 to 800 ± 20 mg COD/L, while the P concentration was about 5 ± 0.5 to 20 ± 2 mg PO_4-P/L, which yielded a COD/P ratio of around 40 mg COD/mg PO_4-P. Influent nitrogen concentration was around 35 ± 5 to 80 ± 5 mg/L as NH_3^+ and 0 ± 0 mg/L as NO_3^- and NO_2^-.

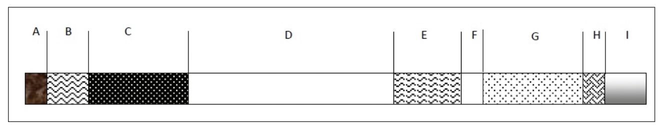

Figure 2: Optimized lab-scale SBR operational condition for biological phosphorus and nitrogen removal

Analytical methods

COD (total and soluble), mixed liquor suspended solid (MLSS), mixed liquor volatile suspended solid (MLVSS), NH_4^+-N (ammonium), NO_2^--N (nitrite), NO_3^--N (nitrate), TKN (total Kjeldahl nitrogen), and TP (total phosphorus as P and PO_4^{3-}-P) were measured according to standard methods (APHA 2005).[17] The dissolved oxygen (DO) concentration was measured using a DO meter (MI-65 Martini Instruments), and the pH value was measured using a pH meter (HACH-Germany).

RESULTS

The pilot plant was operated with different influent wastewater concentrations and hydraulic retention times. There were around 30 separate runs in this study (15 runs as duplicated). The minimum and maximum retention time were 420 and 560 min (7 and 9.3 h), respectively. According to pre-test analysis, the hydraulic retention time (HRT) in the filling, settling, decanting, and idle stages were kept constant, but main metabolic stages of the SBR system was operated with variable HRTs. Table 1 illustrates the different operational times of the lab-scale SBR reactor in this research. The MLSS concentration in the system varied from at least 1500 mg/L to at most 6000 mg/L. Before every running of SBR, the concentration of MLSS was determined, and it was maintained at an accepted range for the SBR system (1500-4000 mg/L). After finishing every run of the system, the mixed liquor was aerated until beginning of another run. The DO level in the mixed liquor was maintained at above 2 mg/L.

Figures 3 and 4 depict the lab-scale SBR efficiencies in phosphorus and nitrogen removal versus various operation times.

Figure 5 illustrates how nitrate and nitrite ions are produced in the aerobic stage; however, the remaining concentration of these ions in the effluent from the SBR reactor is lower than their standard discharge levels of the receiving water. Besides, this lab-scale SBR was more able of removing approximately 99% of soluble COD and 99.5% of TSS in the effluent [Figure 6].

Overall removal efficiencies of the lab-scale SBR reactor are shown in Figure 7. As can be seen from this Figure, the overall removal efficiencies of phosphorus, nitrogen, COD, and TSS were remained stable after stage 11 until the end of the operational stages and there were little changes in the SBR efficiencies in these steps. Therefore, for economical and operational reasons, a short HRT cycle among stages 11-15, cycle 11 with 520 min of HRT, was selected as an optimized operational condition of SBR for effective phosphorus and nitrogen removal [Figure 7].

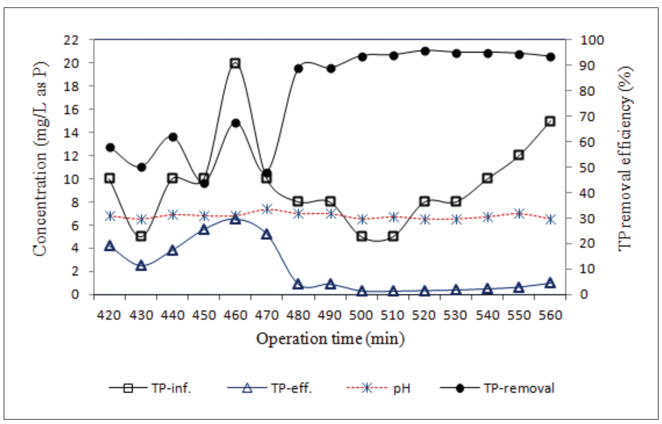

Figure 3: Phosphorus removal rate versus various operational times of lab-scale SBR

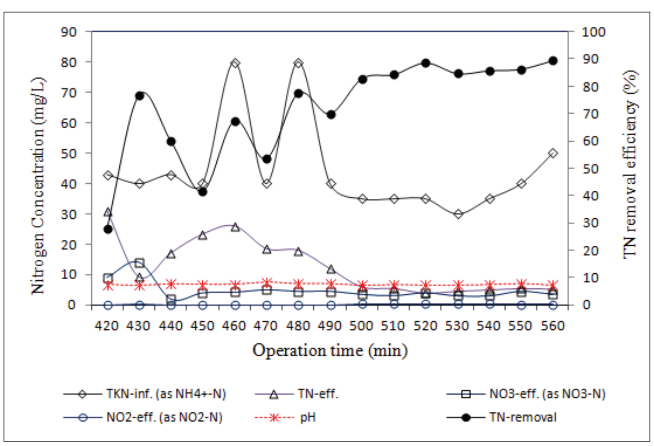

Figure 5: Nitrate and nitrite concentration versus various operational times of lab-scale SBR

DISCUSSION

This lab-scale SBR system was started up with different HRTs in order to achieve enhanced nutrient (P and N) removal. As is shown in Table 1, the operational time in the fill, settle, decant, and idle states was maintained constantly for 15, 90, 10, and 10 min, respectively. But the HRTs in the anoxic (1st and 2nd), anerobic and aerobic (1st and 2nd) stages were changed according to appropriate removal of phosphorus and nitrogen. The pre-anoxic phase before the anerobic phase was considered in this experiment to increase the phosphate uptake capacity. Lee and Jeon investigated on simultaneous biological phosphorus and nitrogen removal with enhanced anoxic phosphate uptake investigated in an anaerobic–aerobic–anoxic–aerobic SBR in the $(AO)_2$ SBR system found that the ratio of the anoxic phosphate uptake to the aerobic phosphate uptake capacity was increased from 11% to 64% by introducing an anoxic phase in an anaerobic–aerobic SBR.[6] Similar to Lee and Jeon, in this study by introducing an anoxic phase in the first stage and before anaerobic phase, enhanced the phosphate release and uptake in following anaerobic and aerobic phases, respectively.

As shown in Figures 3 and 4, average removal rates of P and N during different times of operation were 78% and

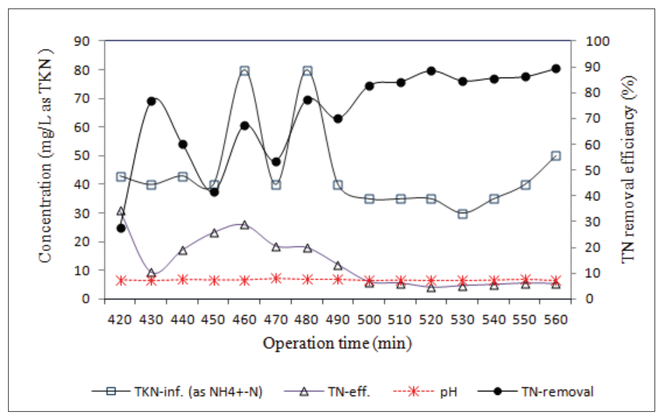

Figure 4: Nitrogen removal rate versus various operational times of lab-scale SBR

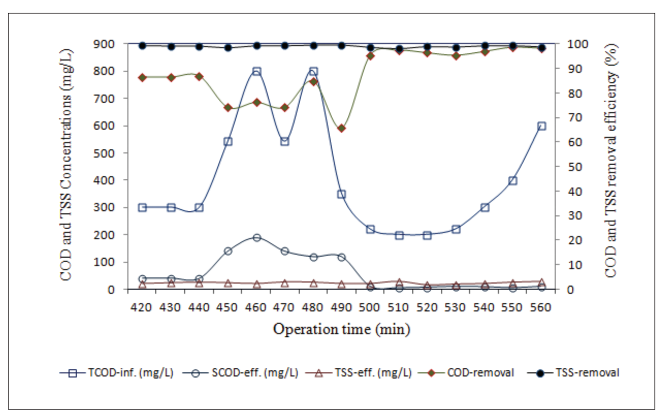

Figure 6: COD and TSS removal rate versus various operational times of lab-scale SBR

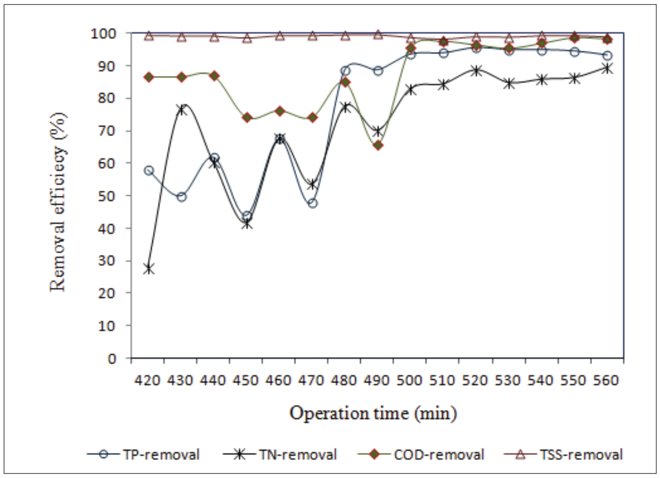

Figure 7: Overall removal efficiencies of phosphorus, nitrogen, TSS, and COD in the lab-scale SBR

72%, respectively. But whatever important in this study was optimization of SBR system to increase the removal rates of phosphorus and nitrogen by improving main process HRTs, namely, pre-anoxic, anerobic, aerobic, anoxic, and post-aerobic operational times. Thus, aaccording to the results, removal rates of P and N were improved by increasing pre-anoxic, anerobic, and aerobic times to at least 30, 90, and 210 min, respectively. In this case, 96% of phosphorus and 89% of nitrogen were removed in the SBR (stages 11 to 15 of SBR operation).

Similar to this study, Obaja *et al.* studied on lab-scale SBR in order to demonstrate the feasibility of using an internal carbon source for biological nitrogen and phosphorus removal in piggery wastewater. They found that the internal C-source used for denitrification had similar effects to acetate. 99.8% of nitrogen and 97.8% of phosphate were removed in the SBR from an initial content in the feed of 900 mg/L ammonia and 90 mg/L phosphate.[3]

As can be seen from Figure 7, the removal rates of P and N remained almost steady and sometimes gradually increased from stages 11 to 15 (i.e., HRT 520-560 min). According to Jeon and Park for enhanced phosphorus removal using the SBR system, the concentration of phosphate in the anerobic stage was increased from 0 to 30 mg/L gradually during 2 h and then decreased to 0 mg/L in the aerobic stage during 3-4 h. Conversely, the concentration of nitrate was increased from 0 mg/L in the anerobic stage to around 8 mg/L in the aerobic stage after 6 h retention time of operation.[18] The phosphorus released in the anaerobic zone is taken up either under anoxic or aerobic conditions by utilizing nitrates or DO as the final electron acceptor.[19,20]

Nitrate can affect phosphate release and lead to reduced efficiency of biological phosphorus removal process. In the anoxic phase, the remaining nitrate concentration was quickly reduced and a considerable amount of phosphate was released. For reduction in the nitrate and/or nitrite ions interference and effective phosphorus removal, a short anoxic phase was beneficial before an anerobic phase.

Akin and Ugurlu found that the anerobic/anoxic phases in a lab scale SBR were capable of removing approximately 80% of the influent PO4-P, 98% NH4-N, and 97% COD at a SRT of 25 days. In the fill/decant phase, anoxic and anerobic conditions prevailed and a large quantity of nitrate was removed in this stage. They concluded that for effective removal of nitrogen and phosphate, a short anoxic phase was essential before an aerobic phase.[20]

For effective removal of phosphorus and nitrogen as well as denitrification in the BNR (biological nutrient removal) system, the COD/TP ratio is an important design parameter and based on Metcalf and Eddy, this ratio should be 33 or higher.[7] In this work, the COD/TP ratio was adjusted at around 40. Also the F/M ratio was determined at around 0.18-0.2.

CONCLUSION

It can be concluded that the enhanced SBR system with first stage of anoxic phase followed by anerobic and aerobic phases has a good capability of removing simultaneous phosphorus and nitrogen in municipal wastewater.

According to the results from different operational cycles of this lab-scale SBR reactor, it can be deducted that effective biological removal of phosphorus and nitrogen from wastewater using SBR depends upon some operational parameters such as HRT, adequate COD/TP ratio, DO concentration, pH, and sufficient MLSS concentration.

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