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Comparison of phosphorus removal efficiency of conventional activated sludge system and sequencing batch reactors in a wastewater treatment plant

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Abstract. The aim of this study was to evaluate the effectiveness application of sequencing batch reactors (SBRs) for phosphorus removal compared to the conventional activated sludge (CAS) treatment system. The results showed that the removal efficiency of phosphorus reached about 99% at wastewater treatment plant with CAS system. At the same time, the maximum phosphorus removal efficiency can be achieved to 88% if the SBRs system operating parameters are optimized. Finally, this study demonstrated that even if granules are not fully developed, the SBR system is working with a good efficiency.

Key words: phosphorus removal, activated sludge process, SBR, aerobic granules, wastewater treatment plant.

INTRODUCTION

Phosphorus (P) and nitrogen (N) are important nutrients known for stimulation of excess growth of plants, algae and some bacteria such as cyanobacteria in surface waters, thus, being responsible for the intensity of eutrophication (Gorham et al., 2017; Yan et al., 2017; Bhagowati & Ahamad, 2018). P is the critical element which affects eutrophication in most fresh waters. Most of the P load comes from large animal farms, fish farming, waste disposal sites and municipal wastewater treatment plants (WWTP) (Tihomirova et al., 2019). As a result, the demand for P removal from wastewater is increasing nowadays (Qiu & Ting, 2014). Therefore, the need for efficient removal of P from wastewaters and regulation of P limit in final effluent before the discharge into watercourses will help to prevent eutrophication of receiving surface water bodies. As a result, to avoid the potential hazard of P pollution to surface waters, the European Economic Community (ECC) has created an urban wastewater treatment directive 91/271/EEC as a framework to specify the minimum wastewater treatment requirements for the discharge of P-containing compounds into receiving waters depending on the size of WWTPs (ECC, 1991). Usually, the measurement of the total phosphorus (TP) concentration is used for discharge criteria. It includes soluble phosphorus (SP) and particulate phosphorus (PP) (Ge et al., 2018). According to the size of the sewage treatment plant, TP values are 2 mg L^{-1} for 10,000–100,000 population equivalents (PE) and 1 mg L^{-1} TP for > 100,000 PE. At the same time, the effluent limit values for WWTPs with pollution load less than 2,000 PE are not regulated by these requirements (ECC, 1991). As a result of a formation of disperse agglomerations, there are a lot of small-size WWTPs without any legal requirements for P removal. Therefore, biological removal of P from the wastewater is still the challenge in small and local WWTPs within Europe. Implementation of new methods to reduce nutrient loadings are necessary, especially for the treatment of runoff waters from agriculture. Sand filters and nutrient binding compounds are not efficient at the moment. Currently, numerous research groups are focusing on combined processes that can be effective for the removal and recovery of P from wastewaters (Bassin et al., 2012; Lochmatter et al., 2013; Yan et al., 2015). As shown, biological P removal methods are more affordable and environmentally friendly than the chemical ones (Manas et al., 2011; Pronk et al., 2015).

Conventional activated sludge (CAS) systems are the most widely applied technologies for biological nutrient (P and N) and organic matter removal from municipal wastewaters worldwide (Meerburg et al., 2015). However, this technology requires high energy consumption and produces huge amount of excessive activated sludge (Gu et al., 2017). The current practice shows that 45–75% of the total plant operation costs are used for intensive aeration (Capodici et al., 2019; Wu et al., 2019), since dissolved oxygen (DO) represents an essential factor for biological processes in WWTPs (Tang et al., 2015). At the same time, the treatment of the excess activated sludge may account for 25–65% of the total plant operation costs (Gu et al., 2017). Therefore, the demand for more cost-efficient and less-occupied technologies is critically important to improve wastewater treatment process sustainability.

Recently aerobic granular sludge (AGS) has been investigated as an alternative to traditional CAS process (De Kreuk, 2006; Nancharaiah & Kiran Kumar Reddy, 2018). AGS technology has been developed to improve the settling properties of the activated sludge and mainly has been applied in the sequencing batch reactor (SBR) systems which have been incorporated into several full-scale domestic WWTPs within Europe (Pronk et al., 2015; Barrios-Hernandez et al., 2020). The operation of an SBR is based on fill-and-draw principles, which typically consist of four steps–fill, aeration, settling and drawing within the same reactor. When compared to traditional activated sludge systems, AGS technology has many advantages, such as excellent settleability, resulting in a short settling time for good liquid-solid separation, stronger granule structure, good biomass retention, high resistance to toxicity and simultaneous P and N removal (Adav et al., 2008; Li et al., 2014). Additionally, AGS technology has smaller space requirements, lower energy consumption and lower overall operational costs. Due to these advantages, it is regarded that AGS technology has a great potential to become one of the most prospective biological wastewater treatment approaches in the future (Zhang et al., 2016).

The objective of this study was to evaluate the effectiveness of the application of SBRs for P removal. Studies were performed at a full scale municipal WWTP in Latvia. Both processes were operated in parallel from August 2017 to April 2018.

MATERIALS AND METHODS

Study site

A pilot-scale SBRs were located in the municipal WWTP in Adazi, Latvia. The influent wastewater was directly introduced into the SBRs from the grit chamber in the

Adazi WWTP. The composition of the influent was within the required ranges (Table 1). The SBRs were directly inoculated with 120 L of activated sludge at the beginning of the experiment and 40 L twice a month taken from an aeration tank at the Adazi WWTP. The seeding sludge had a mixed liquor suspended solids (MLSS) concentration of 3.5–6.1 g L^{-1}, a sludge volume index (SVI) of 136–187 mL g^{-1} and the sludge volume was 520–920 mL L^{-1} after 30 min settling. Monitoring of both processes (AGS at WWTP and SBR in pilot-system) was performed in parallel over a 9 month period with receiving the same influent wastewater.

Table 1. Composition of the municipal wastewater

Parameter, mg L^{-1}	Mean ± 1 S.D.	Range (min – max)
COD	691 ± 410	260–1,920
BOD_5	446 ± 275	150–1,300
SS	293 ± 222	82–1,000
TN	78 ± 26	33–137
TP	9.2 ± 2.9	4.2–15.2
pH	7.8 ± 0.6	6.5–8.6

Pilot-scale SBR set-up and operation

The two identical parallel column reactors with internal diameters of 0.6 m and working volumes of 0.33 m^{-3} were used in this study. The operating flow rate was 5 L min^{-1}. The reactors were aerated by using fine bubble aerators. The dissolved oxygen (DO) concentration was 60 L sec^{-1}. The pilot-scale SBRs with a volumetric exchange ratio of 8% were operated in a fill-draw mode, in successive cycles of 4 h each. One cycle consisted of 5 min feeding, 210 min aeration, 25 min settling and 5 min effluent discharge. Feeding and discharge of wastewater was conducted at one time. The procedures of the reactors operation, including feeding, aeration, setting and discharging, were controlled automatically by a digital process controller (Controller, Adrona). The wastewater was introduced in the top part of the reactors. The effluent was at the height of 1.18 m from the bottom of the reactors.

Sample collection

Wastewater (influent and effluent) samples were collected from a pilot and full-scale systems in plastic carboys (2 L) and stored in a refrigerator (2 °C to 5 °C) after transport. All analysis were performed within 24 h after collection. All wastewater and sludge samples analyses were conducted according to the standard methods (Table 2).

Table 2. Wastewater quality analytical methods

Parameter	Reference
Chemical Oxygen Demand (COD)	LVS ISO 6060:1989
Biochemical Oxygen Demand (BOD_5)	LVS EN 1899–2:1998
Total Nitrogen (TN)	LVS EN ISO 11905–1:1998
Total Phosphorus (TP)	LVS EN ISO 6878:2005 (part 7)
Suspended solids (SS)	LVS EN 872:2007
Mixed liquor suspended solids (MLSS)	LVS EN 872:2007
pH	LVS EN ISO 10523:2012
Sludge volume index (SVI)	APHA, 2005

Determination of the concentration of Total Nitrogen (TN) and Total Phosphorus (TP) were performed with UV–Vis spectrophotometer M501 (Camspec, UK) after sample mineralisation. Multiple repetitions of each sample (n = 3) and control solutions were analysed to obtain the reproducibility of each method.

RESULTS AND DISCUSSION

TP removal

A long-term study was performed in order to evaluate the effectiveness of two technologies in achieving high phosphorus removal efficiency for municipal wastewater, after which the performances of SBR and CAS systems for TP removal were compared (Fig. 1). The results showed that the removal efficiency of TP was higher in CAS process than in SBR. The values of average influent TP of 4.2–9.2 mg L^{-1} decreased in the effluent to 1.2 mg L^{-1} and 3.5 mg L^{-1} in CAS and SBR, respectively.

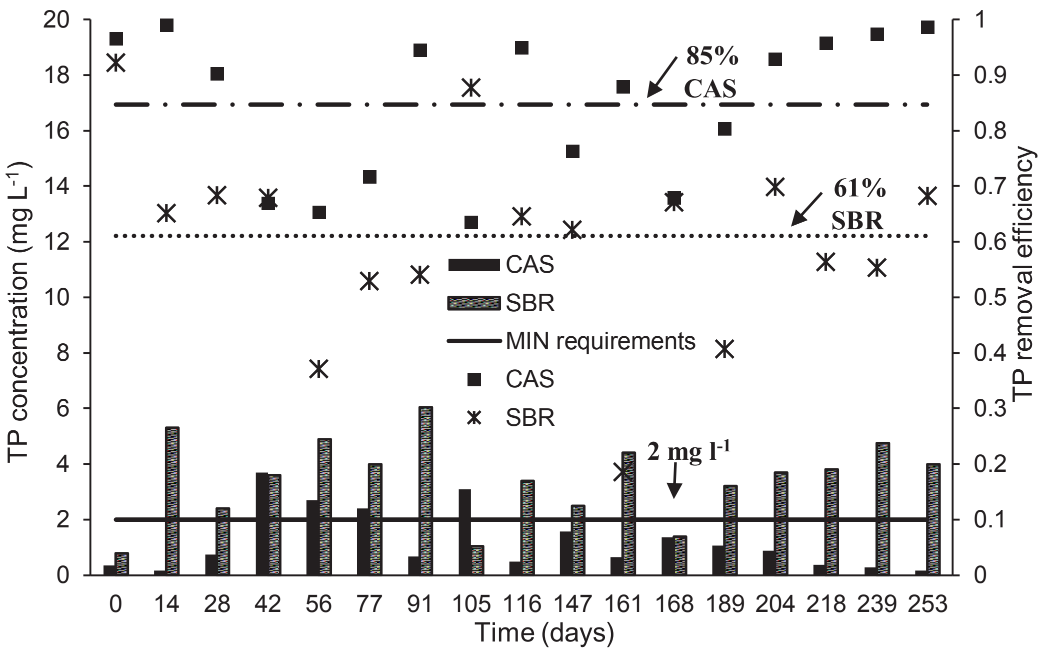

Figure 1. Long-term total phosphorus (TP) effluent concentrations, and its removal efficiencies in CAS and SBR systems. The average TP removal efficiency (▬) in CAS and (▬) SBR.

Thus, demonstrating the average removal efficiency of TP in CAS - 85% and 61% in SBR. At the same time, it should be noted that the TP removal efficiency in SBR reached the maximum value of 88% on day 105, and the discharge requirements were achieved. In contrast to the SBR results on 105 day, the TP of the CAS system was higher than is allowed (Fig. 1).

The physical characteristics such as MLSS and SVI of the sludge in both systems were monitored (Table 3). During the study operation, the average SVI of sludge in CAS system (147 ± 15 mL g^{-1} SS) was two times higher than in SBR (73 ± 26 mL g^{-1} SS). Interestingly, the highest reduction of TP in SBR (on day 105) was achieved when the minimum value of SVI (33 mL g^{-1} SS) and the maximum value of MLSS (1.2 g L^{-1}) was observed.

Table 3. Physical characteristics of sludge in the CAS and the SBR during 9 month operation

Operation duration (day)	MLSS (g L^{-1}) CAS	MLSS (g L^{-1}) SBR	SVI_{30} (mL g^{-1}) CAS	SVI_{30} (mL g^{-1}) SBR
0	5.3	0.6	155	86
14	5.5	0.4	158	71
28	6.0	0.4	142	91
42	5.1	0.8	137	93
56	4.9	0.7	155	43
77	5.0	0.8	168	125
91	5.2	1.1	154	73
105	4.9	1.2	147	33
116	6.1	0.9	138	56
147	5.4	1.1	141	100
168	5.3	0.7	136	86
189	4.5	1.7	164	59
204	5.5	0.8	160	25
218	5.7	1.1	154	55
239	8.5	1.1	108	73
253	7.3	1.1	129	91
Average values	5.6 ± 1	0.9 ± 0.3	147 ± 15	73 ± 26

COD and BOD_5 removal

Fig. 2. shows the values of effluent COD concentrations, and its removal efficiency in CAS and SBR systems during 253 days of operation. The results showed that the average removal efficiency of COD was 94% in CAS and 80% in SBR.

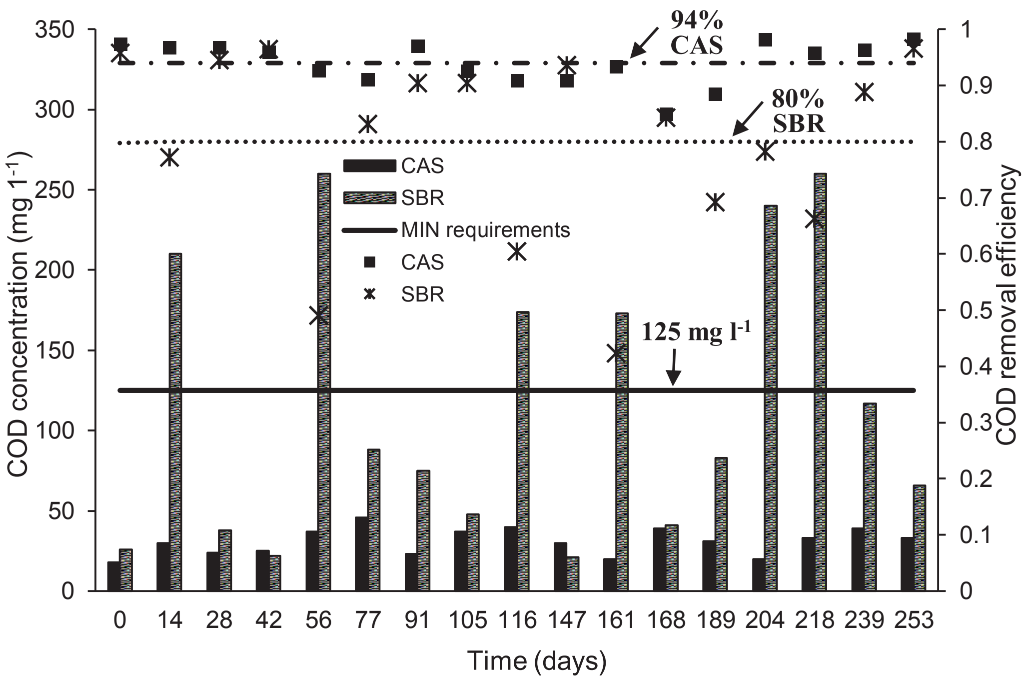

Figure 2. Long-term total Chemical Oxygen Demand (COD) effluent concentrations, and its removal efficiencies in CAS and SBR systems. The average COD removal efficiency (▬) in CAS and (▬) SBR.

Fig. 3. shows the values of effluent BOD_5 concentrations, and its removal efficiency in CAS and SBR systems during 253 days of operation. The results showed that the average removal efficiency of BOD_5 was 99% in CAS and 90% in SBR.

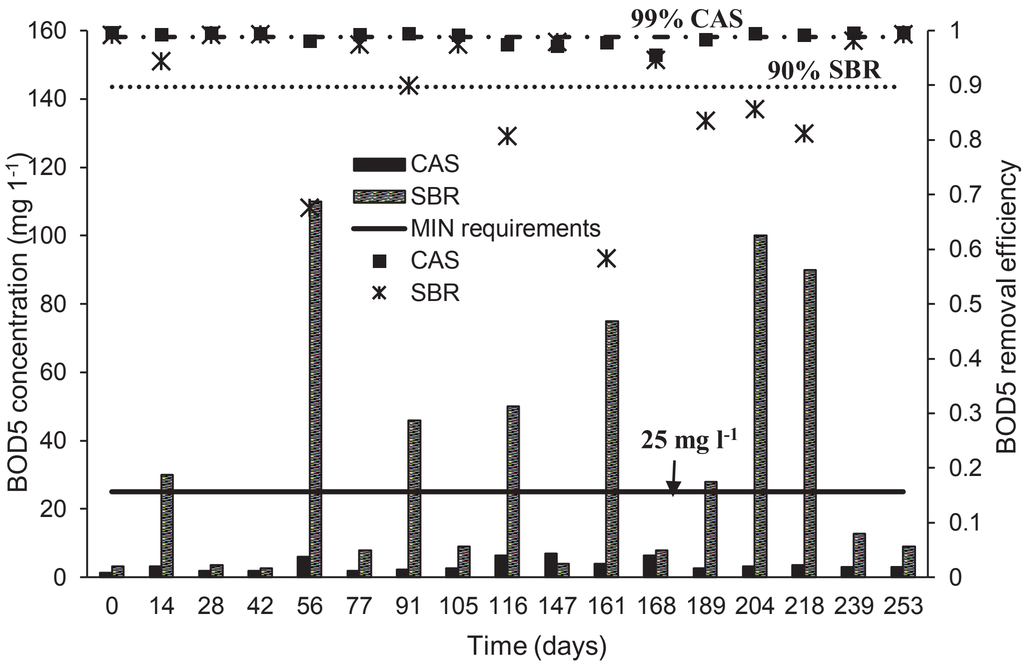

Figure 3. Long-term total Biochemical Oxygen Demand (BOD_5) effluent concentrations, and its removal efficiencies in CAS and SBR systems. The average BOD_5 removal efficiency ( ) in CAS and ( ) SBR.

The COD and BOD_5 removal efficiency were high in SBR at 105 day of the system operation. At the same day, the minimum value of SVI (33 mL g^{-1} SS) and the maximum value of MLSS (1.2 g L^{-1}) in the SBR was observed, the COD removal rate was 90% (at effluent - 48 mg L^{-1}) and the COD removal rate was 97% (at effluent - 9 mg L^{-1}). According to these results, the high COD and BOD_5 removal efficiency presented good performance in both systems. However, this parameter can be optimized for SBR in future investigations, aiming not only high TP, COD, BOD_5 removals, but also energy saving.

Calculations of aeration costs

Modernization of the classic active sludge technology can be connected with reactor system rebuilding or building of new additional reactors in case of increasing wastewater load. Aeration is the main energy consumption stage (Drewnowski et al., 2019). To evaluate the efficiency of the possible technology, aeration costs were calculated. Usually, aeration operates 24 h per day in the classic CAS system, in SBR the system is operated in a periodic cycle regime and aeration is necessary only for 21 h daily (210 min aeration on experimental system, 6 full cycles per day). Main equipment and its technological parameters in the full-scale station Adazi that were used for the calculations are summarised in Table 4. The calculations were based only on the changes of aeration regime.

Electricity consumption (E) per day for full scale aeration system with CAS process can be calculated by the following Eq. (1):

Table 4. The main equipment and its technological paratemers of the Adazi full scale station

Equipment	Piece (n) Technological paratemers	
Aerotank	n = 3 1,500 m^3	
Compresors	n = 3 (type 1) 1,400 $m^3 h^{-1}$ 37.0 kW/ 28.3 kW 24 h / 7 d	n = 6 (type 2) 4.0 kW / 2.75 kW 24 h / 7 d
Mixers	n = 3 3.5 kW/ 2.5 kW 24 h / 7 d	
Sludge dewatering equipment	n = 1 140 kg h^{-1}; 2.6 kW 8 h / 7d	

$$\boldsymbol{E}(\mathbf{CAS}) = (3 \cdot 37.0 \text{ kW} \cdot 24 \text{ h}) + (6 \cdot 2.75 \text{ kW} \cdot 24 \text{ h}) + (3 \cdot 2.5 \text{ kW} \cdot 24 \text{ h}) + (2.6 \text{ kW} \cdot 8 \text{ h}) = 3260.8 \text{ kWh} \quad (1)$$

Electricity consumption (E) per day for full scale aeration system with SBR can be calculated by the following Eq. (2):

$$\mathbf{E}(\mathbf{SBR}) = (3 \cdot 37.0 \text{ kW} \cdot 21 \text{ h}) + (6 \cdot 2.75 \text{ kW} \cdot 21\text{h}) + (3 \cdot 2.5 \text{ kW} \cdot 21 \text{ h}) + (2.6 \text{ kW} \cdot 8\text{h}) = 2855.8 \text{ kWh} \quad (2)$$

CAS ekspluatation costs per day (EURd (CAS)) can be calculated by Eq. (3):

$$\mathbf{EURd}\ (\mathbf{CAS}) = 3260.8 \text{ kWh} \cdot 0.12 \text{ kWh EUR}^{-1} = 391.3 \text{ EUR} \quad (3)$$

SBR ekspluatation costs per day (EURd (SBR)) can be calculated by Eq. (4):

$$\mathbf{EURd}\ (\mathbf{CAS}) = 2855.8 \text{ kWh} \cdot 0.12 \text{ kWh } EUR^{-1} = 342.7 \text{ EUR} \quad (4)$$

CAS ekspluatation costs per year (EURy (CAS)) can be calculated by Eq. (5):

$$\mathbf{EURy}\ (\mathbf{CAS}) = 391.3 \text{ EUR} \cdot 365 \text{ dn} = 142823.0 \text{ EUR} \quad (5)$$

SBR ekspluatation costs per year (EURy (SBR)) can be calculated by Eq. (6):

$$\mathbf{EURy}\ (\mathbf{SBR}) = 342.7 \text{ EUR} \cdot 365 \text{ dn} = 125084.0 \text{ EUR} \quad (6)$$

Calculation of economy (E) can be calculated by Eq. (7):

$$\mathbf{E} = (142823.0 \text{ EUR} - 125084.0 \text{ EUR})/(142823.0 \text{ EUR}) \cdot 100\% = 12\% \quad (7)$$

Each of the CAS reactors at full scale WWTP is equipped 3 compressors and one mixer. The exploitations costs per year are calculated by Eq. (8). Taking into account the fact, that SBR type reactors take up less space (up to 75% smaller area), it can be predicted that only one compressor will be necessary for the aeration. Thus, the predicted economy can be calculated by following Eqs (9–12).

Predicted CAS exploitations costs per year for full scale aeration system with CAS process (EURy (CAS1)p) can be calculated by the Eq. (8):

$$\mathbf{EURy\ (CAS1)p} = \mathrm{EURy\ (CAS)/3} = 47607.7\ \mathrm{EUR} \quad (8)$$

Predicted electricity consumption (Ep) per day for full scale aeration system with SBR can be calculated by the following Eq. (9):

$$\mathbf{E(SBR)p} = (1 \cdot 37.0\ \mathrm{kW} \cdot 21\mathrm{h}) + (12.5\ \mathrm{kW} \cdot 21\ \mathrm{h}) + \frac{(2.6\ \mathrm{kW} \cdot 8\ \mathrm{h})}{3} = 836.4\ \mathrm{kW} \quad (9)$$

Predicted SBR exploitations costs per day (EURd (SBR)p) can be calculated by the Eq. (10):

$$\mathbf{EURd\ (CAS)p} = 836.4\ \mathrm{kWh} \cdot 0.12\ \mathrm{kWh\ EUR}^{-1} = 100.4\ \mathrm{EUR} \quad (10)$$

Predicted SBR exploitation costs per year (EURy (SBR)p) can be calculated by the Eq. (11):

$$\mathbf{EURy\ (SBR1)p} = 100.4\ \mathrm{EUR} \cdot 365\ \mathrm{dn} = 36634.3\ \mathrm{EUR} \quad (11)$$

Calculation of economy due to the equipment amount (Eep.) (12):

$$\mathbf{Eeq.} = (47607.7\ \mathrm{EUR} - 36634.3\ \mathrm{EUR})/(47607.7\ \mathrm{EUR}) \cdot 100\% = 23\% \quad (12)$$

Full market search on appropriate equipment was not performed within this study. To calculate the exploitation costs and economy, the technological parameters of existing equipment were taken into account. Therefore, the estimations can be regarded as approximate and minimal. In case of full scale-larger size equipment, the economy is expected to be higher.

CONCLUSIONS

This study demonstrated that the removal efficiency of phosphorus reached about 99% at wastewater treatment plant with CAS system. At the same time, the maximum removal efficiency was 88% using SBRs, when the operating parameters were optimized (MLSS - 1.2 g L^{-1} and SVI - 33 mL g^{-1} SS). But, the SBR system has a flexibility to modify the process control conditions during the operational phases that allows SBR facilities to adapt to changing influent conditions and achieve effluent water quality parameters. The obtained results showed that AGS treatment is effective in biological phosphorus removal and has a good application potential in treatment of municipal wastewater even if stable aerobic activated granules have not developed. To conclude, the proposed SBRs system with the operation of the aeration system allows to reduce about 23% of the operating costs at WWTP.

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