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Model-Based investigation of the effects of reactors' hydraulic retention times on phosphorus removal efficiency in an AO process

Bir AO prosesinde reaktörlerin hidrolik bekletme sürelerinin fosfor giderim verimi üzerindeki etkilerinin modelleme yoluyla incelenmesi

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Abstract

This study presents the results of a simulation work performed using an activated sludge model to investigate the effects of reactors' hydraulic retention times (HRT) on phosphorus removal in a hypothetical anaerobic-oxic (AO) process. The simulations were performed for low, medium, and high influent phosphorus loads corresponding to influent C/P ratios of 100/1.0, 100/1.5, 100/2.0. For each of influent phosphorus loads, various anaerobic volume fractions (AVF) between 0.125 and 0.625 were used to test the response of the process that was investigated as a result of the change in hydraulic retention times. Additionally, removal efficiencies for chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS) were also calculated. As a result of the study, maximum COD removal efficiencies for 100/2.0, 100/1.5 and 100/1.0 influent C/P ratios were determined as 91.8% for 0.250 AVF (for 100/2.0 and 100/1.5), and 91.7% for both 0.125 and 0.250 AVF, respectively. In all influent C/P ratios, the maximum TN removal efficiency was determined as 56.3% at 0.625 AVF, and the maximum TSS removal efficiency was determined as 93.3% at 0.125 AVF. Maximum TP removal efficiencies were determined as 92.8%, 90.8% and 86.2% for 100/2, 100/1.5 and 100/1 input C/P ratios at 0.375 AVF, respectively. Results showed that total phosphorus (TP) removal efficiency is determined by both influent C/P ratio and AVF in AO process. Of these, the effect of AVF is more prominent. For efficient removal of phosphorus, AVF ratios of 0.25 to 0.375 should be employed.

Keywords: Activated sludge model, AO process, Reactor volumes, Phosphorus removal.

Öz

Bu çalışmada, bir kuramsal anaerobik-oksik (AO) prosesinde reaktörlerin hidrolik bekletme sürelerinin (HRT) fosfor giderimi üzerindeki etkilerinin bir aktif çamur modeli kullanılarak simülasyonuna ilişkin bir çalışmanın sonuçları sunulmuştur. Simülasyonlar, C/P oranları sırasıyla 100/1.0, 100/1.5 ve 100/2.0 değerlerine karşılık gelen düşük, orta ve güçlü giriş fosfor yüklerinde gerçekleştirilmiştir. Giriş fosfor yüklerinin her biri için 0.125 ile 0.625 arasında değişen anaerobik hacim fraksiyonlarında (AHF) denemeler yapılarak HRT değişimi için prosesin tepkisi incelenmiştir. Ayrıca, kimyasal oksijen ihtiyacı (KOİ), toplam azot (TN), toplam fosfor (TP), ve askıda katı madde (AKM) için giderim verimleri de hesaplanmıştır. Çalışmada, 100/1.0, 100/1.5 ve 100/2.0 giriş C/P oranlarındaki en yüksek KOİ giderim verimleri 0.250 AHF'de %91.8 (100/2.0 ve 100/1.5 için) ve 0.125 ile 0.250 AHF'de %91.7 olarak belirlenmiştir. Tüm giriş fosfor yükleri için en yüksek TN giderim verimi 0.625 AHF'de %56.3, en yüksek AKM giderim verimi ise 0.125 AHF'de %93.3 olarak hesaplanmıştır. En yüksek TP giderim verimleri 100/1.0, 100/1.5 ve 100/2.0 giriş C/P oranları için sırasıyla %92.8, %90.8 ve %86.2 olarak, 0.375 AHF'de gözlenmiştir. Sonuçlar, toplam fosfor (TP) giderim veriminin giriş C/P oranı ve anaerobik hacim fraksiyonuna (AHF) bağlı olduğunu ortaya koymuştur. Bunlarda AHF'nin etkisi daha baskındır. Etkin fosfor giderimi için AHF'nin 0.250 ile 0.375 arasında tutulması uygun olacaktır.

Anahtar kelimeler: Aktif çamur modeli, AO prosesi, Reaktör hacimleri, Fosfor giderimi.

1 Introduction

Phosphorus is an essential nutrient for most life forms. It is also frequently encountered in industrial manufacturing and in the structure of pesticides [1]. Sewage discharge (discharges from wastewater treatment plants) and agricultural runoff are the main sources of phosphorus releases into the environment and it can cause undesirable eutrophication in receiving water [2]-[6]. Therefore, phosphorus removal is one of the key objectives of treatment operations. Accordingly, effective phosphorus removal is of great importance for the protection of receiving water bodies [7].

For many years, various processes and techniques have been developed for phosphorus removal from wastewater, as well as existing processes have been optimized depending on the changing wastewater characterization [8]. Biological treatment for phosphorus removal is a more cost-effective method compared to chemical treatment [9]. In addition, thanks to biological treatment, the accumulation of different chemicals formed by chemical treatment in receiving water is prevented [10]. Various biological treatment processes are used for the removal of phosphorus in municipal wastewater, such as the five-stage Bardenpho process, the anaerobic/anoxic/oxic (A^2/O) process, the University of Cape Town (UCT) process, the anaerobic/oxic (AO) process etc. [11]-[14]. Additionally, biological phosphorus removal efficiency depends on volatile fatty acid (VFA) potential in wastewater [15]. High concentrations produced out of readily degradable organic matter (soluble and degradable COD) will enable anaerobic tanks to be designed for biological phosphorus removal in smaller volumes. On the other hand, content for lower wastewaters, higher anaerobic volume will be needed to ensure efficient release of phosphorus. Therefore, the hydraulic retention time of the anaerobic reactor will increase [16].

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In biological treatment, many anaerobic and aerobic microorganisms are involved in the removal of various nutrients. In addition, this treatment can result in high costs as it is a slow process and large areas are required for the treatment [10]. In this context, for the design and operation of the biological treatment plant to get efficient results, it is necessary to collect data about the plant and the process through various experiments. Considering the fact that sampling and experimentation for wastewater characterization and processes that take place in the treatment system requires tiring and expensive procedures [17], mathematical models established based on collective knowledge and experience from previous studies provide easier, faster, and cheaper solutions. Besides, some of the objectives in an optimization studies may require changing the configuration and reactor volumes in an installed treatment system, which is usually impossible or at least not feasible in most cases. Therefore, the use mathematical models is encouraged in cases like testing various anaerobic and aerobic volumes in a treatment system for optimization purposes. Regarding the objectives of current study, the authors considered testing various volumes of process reactors in the hope that an optimum set of hydraulic retention times can be obtained through use of activated sludge models. To authors' knowledge no previous studies have been performed for this purpose.

The first of the frequently used activated sludge models (ASM) is ASM1 model developed by [18]. This model is described by the reactions of heterotrophic bacteria that use carbonaceous organics under aerobic conditions and autotrophic nitrifying bacteria that oxidize ammonia to nitrate under anoxic conditions [18],[19]. The second model, ASM2, is a more advanced model that includes bacteria that remove phosphorus under anaerobic, anoxic, and aerobic conditions [20]. The third generation of the models, the ASM3, that include oxygen consumption, sludge production, nitrification, denitrification, and phosphorus removal [21]. After, many models were developed such as the Bio-P module [22], the extended ASM3 model etc. [23].

The aim of this study is to investigate the effect of hydraulic retention times (HRT) on phosphorus removal in an AO process by simulations using ASM no. 3 extended with EAWAG (Swiss Federal Institute of Aquatic Science and Technology) bio-P module. For this purpose, different volumes were set for anaerobic and aerobic tanks, with a total hydraulic retention time of four hours in an AO process and phosphorus removal efficiencies were calculated according to wastewater quality parameters.

2 Materials and methods

2.1 Activated sludge process

Phosphorus removal performance of a hypothetical AO (anaerobic-oxic) process was simulated by activated sludge modeling. The effects of various sets of anaerobic and aerobic volumes of the process on phosphorus removal efficiency were investigated under three different influent (primary effluent) phosphorus loads. The AO process was designed for an influent wastewater flowrate of 3600 m^3/h and a total HRT of 4 hours. For each of influent phosphorus loads, five different anaerobic volume fractions (AVF-0.125, 0.25, 0.375, 0.5, 0.625) were used to test the response of the process (Table 1). A secondary sedimentation unit with a total surface area of 6480 m^2 and a side-wall depth of 3 m was attached to the process reactors to keep mixed liquor within the process. The return activated sludge (RAS) ratio was 80%, and the sludge retention time (SRT) of the process was set to around 4 days by adjusting the waste activated sludge (WAS) flowrate. The split ratio of the secondary sedimentation basin, which is defined by the ratio of WAS flowrate to influent flowrate, was around 2% to keep the SRT around the desired value of 3.5 days. Shao et al. [24] in their study with SBR using campus wastewater; determined that phosphorus removal efficiency was below 40% at 0.5- and 1-day SRT, below 60% at 2 days SRT, but above 90% at 3 and 4 days SRT. Chan et al. [25] reported in their study with SBR that there was a decrease in phosphorus release and uptake at SRT less than 3 days. A flowchart of the system is shown in Figure 1, and the design specifications are given in Table 1.

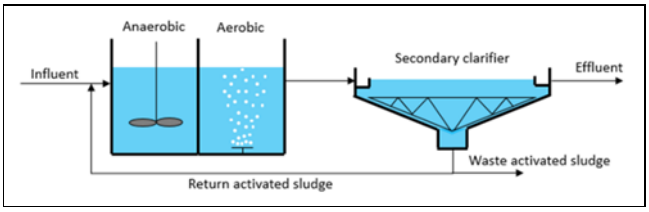

Figure 1. Flowchart of the AO process.

Table 1. Design specifications of activated sludge process.

Dimensioning	Value
Process reactors	
Anaerobic HRT	Case 1: 0.5 h (1800 m^3) Case 2: 1.0 h (3600 m^3) Case 3: 1.5 h (5400 m^3) Case 4: 2.0 h (7200 m^3) Case 5: 2.5 h (9000 m^3)
Aerobic HRT	Case 1: 3.5 h (12600 m^3) Case 2: 3.0 h (10800 m^3) Case 3: 2.5 h (9000 m^3) Case 4: 2.0 h (7200 m^3) Case 5: 1.5 h (5400 m^3)
Total HRT	4 h (14400 m^3)
AVF	0.125, 0.25, 0.375, 0.5, 0.625
Return activated sludge (RAS) flowrate	2880 m^3/h (80%)
Waste activated sludge (WAS) flowrate	75 m^3/h (2%)
Sludge retention time (SRT)	Around 3.5 days
Secondary clarifier	
Total surface area	6480 m^2
Surface loading	1 m^3/m^2.d
Side-wall depth	3 m
Hydraulic retention time	3 h
Inlet depth	1.5 m from surface

2.2 Wastewater characterization

The purpose of the simulations was to compare steady-state phosphorus removal performance of the process under various influent phosphorus concentrations. For this purpose, several influent carbon-to-phosphorus (C/P) ratios were used to simulate all of the three cases presented in Table 2 as 100/1.0, 100/1.5, 100/2.0. In all simulations, chemical oxygen demand (COD) of influent was assumed to be 400 g/m^3, and influent total Kjeldahl nitrogen (TKN) of 20 g/m^3 corresponding to a carbon-to-nitrogen (C/N) ratio of 100/5. Total phosphorus (TP) concentration of the influent wastewater in each simulation were calculated using predetermined C/P ratios. This way, a total of 15 simulations were run (5 cases times 3 TP concentrations). The data summarized in Rossle and Pretorius [26] was used for calculating influent component concentrations in the activated sludge model. Wastewater characterization used in simulations are shown in Table 2.

Table 2. Influent wastewater characterization.

Characterization	Concentration
Conventional characteristics	
Chemical oxygen demand (COD)	400 g/m^3 as COD
Total Kjeldahl nitrogen (TKN)	20 g/m^3 as nitrogen
Total nitrogen (TN)	20 g/m^3 as nitrogen
Total phosphorus (TP)	4, 6, 8 g/m^3 as phosphorus
Total suspended solids (TSS)	180 g/m^3
Alkalinity	5 mol/m^3 as HCO_3
Temperature	20 °C
Activated sludge model components	
Inert soluble organics	20 g/m^3 as COD
Readily biodegradable organics	140 g/m^3 as COD
Inert particulate organics	20 g/m^3 as COD
Slowly biodegradable organics	220 g/m^3 as COD
Ammonia+ammonium nitrogen	7.5 g/m^3 as nitrogen
Nitrite+nitrate nitrogen	0
Phosphate phosphorus	2.7, 4.7, 6.7 g/m^3 as phosphorus
C/N/P	100/5/1.0, 100/5/1.5, 100/5/2.0

2.3 Simulation tool

An MS Excel Visual Basic for Applications (VBA) tool, developed for educational purposes by one of the authors of this paper, was used in simulations. The tool employs Activated Sludge Model No. 3 (ASM3) by Gujer et al. [21] extended with the EAWAG bio-P module by Rieger et al. [22], together called ASM3p. The extended model contains 23 processes including several of each heterotrophic, autotrophic and phosphorus removal processes as well as 16 individual components, 8 of which is in dissolved form and 8 is in particulate form. The relationships between processes and individual components are defined with 26 stoichiometric and 44 kinetic parameters. The tool incorporates a one-dimensional, ten-layered secondary sedimentation model with Takacs double-exponential model [27] for settling velocities. In all simulations default values of stoichiometric, kinetic, and settling parameters were used.

The simulation tool is an improved version of bioXL [28] and bioXL3 [29] and is designed with a user-friendly and easy-to-use interface. It has extensive error handling procedures that produce proper warning messages in case of erroneous entries. The tool allows the topology of the activated sludge process by reactors and links connecting these reactors. It assumes complete-mixing in all reactors and is capable of performing steady-state and unsteady-state solutions for the system.

Unsteady-state simulations for all of influent wastewater characteristics in all cases of reactor volume distributions were performed separately using the tool until steady-state conditions have been reached, and steady-state effluent concentrations from each simulation were evaluated in this study.

3 Results

Simulations were performed on the AO process described in previous section using activated sludge model to obtain steady-state effluent concentrations for low, medium, and high influent phosphorus loads corresponding to influent C/P ratios of 100/1.0, 100/1.5, 100/2.0. The effect of AVF varying between 0.125-0.625 depending on different anaerobic and aerobic reactor hydraulic retention times was investigated. Simulations were performed using a step size of 30 seconds until steady-state conditions are reached which took place in 50 to 200 days of simulation depending on the initial component concentrations in reactors. A total of 15 simulations were performed. In all simulations, the sludge retention time (SRT) was calculated between 3.6 and 3.7 days. Although the main purpose of this study is phosphorus removal performance of an AO process, removal efficiencies for chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS) were also calculated.

Figure 2 shows COD, TN, and TSS removal efficiencies for various anaerobic volume fractions averaged over different influent phosphorus concentrations. The standard deviations and average values are added in Figure 3.

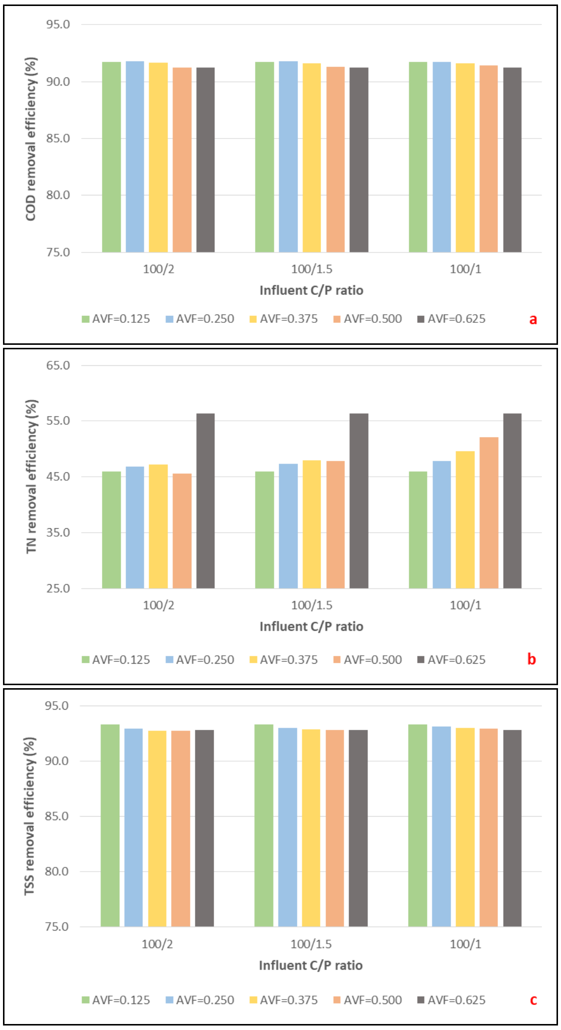

Figure 2. Removal efficiencies for various anaerobic volume fractions (AVFs) and various influent C/P ratio. (a): Chemical oxygen demand (COD), (b): Total nitrogen (TN), (c): Total suspended solids (TSS).

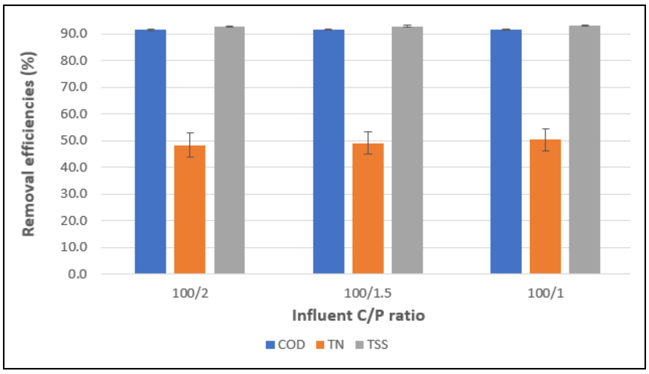

Figure 3. Averages of removal efficiencies with standard deviations for various influent C/P ratio.

Results showed that COD removal efficiencies changed within a very narrow range from 91.3% to 91.8% Figure 2(a) with an average value of 91.5% ± 0.3% Figure 3 at influent C/P ratio of 100/2.0, from 91.3% to 91.8% Figure 2(a) with an average value of 91.5% ± 0.2% Figure 3 at influent C/P ratio of 100/1.5 and from 91.3% to 91.7% Figure 2(a) with an average value of 91.5% ± 0.2% Figure 3 at influent C/P ratio of 100/1.0 which suggests that influent phosphorus concentrations do not affect COD removal efficiency of an AO process. Although there was a reduction in COD removal efficiency with increasing anaerobic volume fraction (AVF), this change was negligible. In a study by Wang et al. [30], in which the A/O process was operated as one chamber of anaerobic followed by three chambers of aerobic at SRTs of 4-6 days and temperatures of 16-26 °C, the effluent COD concentrations were 43.1 mg/L on average during the whole operating period. TN removal efficiencies were calculated between 45.5% and 56.3% Figure 2(b) with an average value of 48.3% ± 4.5% Figure 3 at influent C/P ratio of 100/2.0, between 46.0% and 56.3% Figure 2(b) with an average value of 49.1% ± 4.1% Figure 3 at influent C/P ratio of 100/1.5, and between 45.9% and 56.3% Figure 2(b) with an average value of 50.4% ± 4.0% Figure 3 at influent C/P ratio of 100/1.0. TN removal efficiencies were almost constant for AVFs less than 0.5, while a drastic increase was observed at AVF equal to 0.5 followed by a considerable increase with the increase of AVF up to 0.625. In a study by Sheng et al. [31] performed in a full-scale wastewater treatment plant that has an AO process configuration, TN removal efficiency was reported as 42.5%±22.9%, and possible reason for the reported removal efficiencies was reported as the low COD/TN ratios in influent. TSS removal efficiencies were similar to COD removal efficiencies, ranging from 92.7% to 93.3% Figure 2(c) with an average value of 92.9% ± 0.2% Figure 3 at influent C/P ratio of 100/2.0, from 92.8% to 93.3% Figure 2(c) with an average value of 93.0% ± 0.2% Figure 3 at influent C/P ratio of 100/1.5, and from 92.8% to 93.3% Figure 2(c) with an average value of 93.0% ± 0.2% Figure 3 at influent C/P ratio of 100/1.0 . According to the obtained results COD, TN, and TSS removal efficiencies of an AO process is considered to be independent from influent phosphorus concentrations while the effects of anaerobic volume fraction on COD, TN, and TSS removal efficiencies are very limited.

Figure 4 shows calculated TP removal efficiencies for varying AVFs at influent C/P ratios of 100/1, 100/1.5 and 100/2. Results showed that, unlike COD, TN, and TSS removal, TP removal was significantly affected by both influent C/P ratio and anaerobic volume fraction. TP removal efficiencies were calculated between 25.5% and 92.8% Figure 4(a) with an average value of 59.9% ± 32.7% Figure 4(b) at influent C/P ratio of 100/2.0, between 34.0% and 90.8% Figure 4(a) with an average value of 64.3% ± 27.2% Figure 4(b) at influent C/P ratio of 100/1.5, and between 50.8% and 86.2% Figure 4(a) with an average value of 70.6% ± 16.0% Figure 4(b) at influent C/P ratio of 100/1.0. Results also suggested that efficient phosphorus removal can be accomplished when 25% to 37.5% of total HRT of reactors is reserved for anaerobic processes. Phosphorus removal fails when anaerobic volume fraction is less than 0.250 or higher than 0.375. It is clear that TP removal efficiency increases with increasing influent C/P ratio for AVFs of 0.250 to 0.375. In contrast, the efficiency decreases with increasing influent C/P ratio. The reason for this is that removal efficiency is calculated as the ratio of the concentration removed to influent concentration. It was reported by Qiu et al. [32] that TN and TP removal efficiencies in Jizhuangzi wastewater treatment plant in Tianjin, which is operated as an AO process, are 55% and 90%, respectively, and that on-line sensors can be used for process optimization.

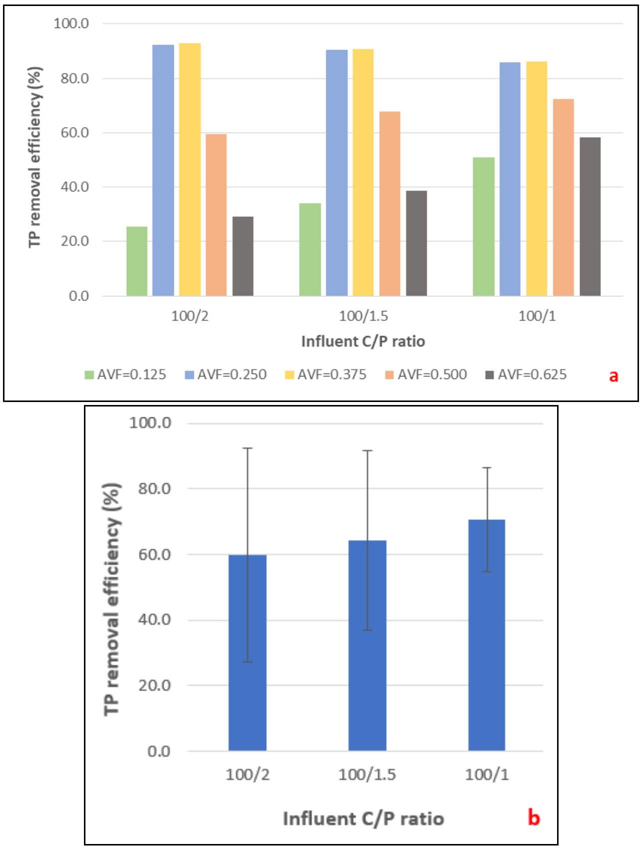

Figure 4(a): Total phosphorus removal efficiencies for various anaerobic volume fractions (AVFs) at various influent C/P ratios. (b): Averages of removal efficiencies with standard deviations for various influent C/P ratio.

4 Conclusions

This paper summarizes the results of a simulation work for the investigation of the effects of reactors' hydraulic retention times (HRT) in an AO process on phosphorus removal efficiency. Activated sludge model no. 3 (ASM3) extended with biological phosphorus removal processes was used in the simulations. Four scenarios were built based on anaerobic and aerobic volumes of the process with a total HRT of 4 hours. Besides, three different carbon-to-phosphorus (C/P) ratios in the influent were used to test the system's response to various influent phosphorus loadings. A total of 15 simulations were performed, and steady-state effluent concentrations of phosphorus species (PO_4-P, TP) were used to assess the system's phosphorus removal performance. Following conclusions can be withdrawn from the results of this study:

- Chemical oxygen demand (COD) removal efficiency is a function of neither influent C/P ratio nor anaerobic volume fraction (AVF) in AO process. It stays relatively constant in all cases,
- Total nitrogen (TN) removal efficiency is not a function of influent C/P ratio, however, AVF has a clear effect on TN removal efficiency of AO process,
- Total suspended solids (TSS) removal efficiency shows a similar trend to COD and is under the influence of neither influent C/P ratio nor AVF in AO process,
- Total phosphorus (TP) removal efficiency is determined by both influent C/P ratio and AVF in AO process. Of these, the effect of AVF is more prominent. For more efficient removal of phosphorus, AVF ratios of 0.25 to 0.375 should be employed. Outside this range, phosphorus removal is considerably reduced.

5 Authors contributions statements

Sümeyye YAŞAR performed the main simulation works. She performed literature search. Also, she prepared the charts in the paper. She helped evaluating the results of the simulations. She wrote introduction part of the paper. Neslihan MANAV DEMİR came up with the idea of this simulation work. She prepared the scenarios that are simulated in this work. She evaluated simulation results. She helped writing most parts of the paper, and she performed all editing tasks. Elif Burcu ATÇI helped the simulation works, and she also contributed to the writing of the paper. Selami DEMİR developed the simulation tool. He helped generating the simulation scenarios. Also he contributed to the writing of the paper in sections related with the tool.

6 Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared.

There is no conflict of interest with any person or institution in the article prepared.

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