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Research Article

COMPARISON OF PERFORMANCES OF BIOLOGICAL NUTRIENT REMOVAL SYSTEMS FOR MUNICIPAL WASTEWATER TREATMENT

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ABSTRACT

Performance of wastewater treatment processes depends on many factors including wastewater characteristics, environmental conditions and operating parameters. Several treatment processes have their own advantages and disadvantages in terms of treatment performance. Performances of anaerobic/anoxic/oxic (A^2O), five-stage Bardenpho (fsB), University of Cape Town (UCT), and modified UCT processes for biological nutrient removal from municipal wastewaters were evaluated at various C:N:P ratios in primary effluent by keeping all other parameters identical to each other in each process. The comparison was based on steady-state removal efficiencies for chemical oxygen demand (COD), total Kjeldahl Nitrogen (TKN), total nitrogen (TN), and total phosphorous (TP). Simulations were performed using an MS Excel Visual Basic for Applications (VBA) tool based on Activated Sludge Model No.3 extended with biological phosphorous removal processes. Simulation results indicated that, for low-to-mid influent TKN/COD ratios, fsB process shows the best performance in terms of TN and TP removal. On the other hand, modified UCT process can be the best selection at high influent TKN/COD ratios if only phosphorous removal is of concern. Five-stage Bardenpho process must be selected for both nitrogen and phosphorous removal no matter the influent C:N:P ratio is.

Keywords: Enhanced municipal wastewater treatment, biological nutrient removal, nitrogen removal, phosphorous removal, process configurations, activated sludge modeling.

1. INTRODUCTION

A great number of process configurations exist for the treatment of residential and municipal wastewaters [1]. These process configurations usually comprise the first and the second stage of treatment as primary, secondary, and sometimes tertiary stages. Primary treatment usually consists of screening, grit removal, and primary sedimentation for the purpose of removing non-biodegradable materials prior to biological treatment as well as reducing the organic loading that upsets the biological treatment units. On the other hand, the configuration of the secondary treatment or existence of tertiary treatment systems differ from one process to another depending on several factors such as treatment objectives, wastewater characteristics, costs of investment and operation [2]. Today's biological wastewater treatment systems are usually built for both nitrogen and phosphorous removal.

A number of well-known biological nutrient removal (BNR) systems exist including A^2O [3, 4], five-stage Bardenpho (fsB) [5, 6], standard and modified versions of UCT (University of Cape

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Town) [7, 8], the VIP (Vir ginia Initiative Plant) [7], and Johannesburg processes [9, 10]. All of these processes have different combinations of anaerobic, anoxic, and aerobic reactors, and their own advantages and disadvantages for specific treatment goals.

The A²O process is the fundamental form of process configurations for BNR systems [11]. It consists of an anaerobic-anoxic-aerobic reactor configuration [12] followed by a secondary clarifier [13, 14]. The anaerobic step in the process is the main step that receives the influent wastewater (usually primary effluent) and the return activated sludge (RAS). The purpose of this step is hydrolysis of slowly biodegradable organics into readily biodegradable organics for subsequent steps. The effluent from anaerobic step is taken to the anoxic step, which also receives recycled nitrate from the aerobic step. The purpose of the anoxic reactor is the reduction of nitrite and nitrate nitrogen (NO_2^--N and NO_3^--N) into nitrogen gas (N_2) [15] by heterotrophic bacteria including phosphorous accumulating organisms (PAOs), which are also responsible for accumulating soluble phosphorous (PO_4^{3-}-P) in biomass to be removed in secondary clarification step. Besides, most of biodegradable organics are oxidized in this reactor. The purpose of the aerobic reactor is rather the oxidation of ammonia nitrogen (NH_3-N) into NO_2^--N and NO_3^--N. Besides, remaining biodegradable materials are removed in this step prior to secondary clarification. The hydraulic retention times (HRTs) of the anaerobic, anoxic, and aerobic steps are usually within the ranges of 0.5-1.5, 0.5-1.0, and 4-8, respectively, and the sludge retention time (SRT) of the process is usually between 3 and 60 days [15] or 5 and 25 days. Reported advantages of A²O process include high alkalinity surplus in aerobic reactor for nitrification, good settling sludge, cost-effectiveness [11], and high nitrogen removal efficiencies although nitrogen removal is usually limited by internal recycle (IR) ratio. A major disadvantage of the process is reported as high nitrite and nitrate concentrations recycled to the anaerobic reactor with RAS. In A²O process, organic matter is reduced by phosphorous accumulating organisms under anaerobic conditions, resulting in low organic substrate concentration for denitrifiers under anoxic conditions [11]. Rong et al [16] reported a continuous A²O process operated with 100% RAS ratio and 300% IR ratio at an SRT of 20 days, in which they obtained 71.63%, 72.63%, and 78.79% removal efficiencies for chemical oxygen demand (COD), total nitrogen (TN), and total phosphorous (TP), respectively. In another study in which Zong et al [17] applied various HRTs between 10.5 and 52.5 hours at RAS and IR ratios of 100% and 200%, respectively, the authors reported that the optimum HRT for the process was 25.26 hours.

The fsB process adds two more steps to the A²O process with the configuration of anaerobic-anoxic1-aerobic1-anoxic2-aerobic2 reactors followed by a secondary clarifier [18]. The purpose of the second anoxic reactor in this process is further reduction of nitrite and nitrate in the effluent of the first aerobic reactor, and thus improving nitrogen removal efficiency. Wıth the addition of a second anoxic reactor, nitrite and nitrate concentration recycled to the anaerobic reactor with RAS is also reduced, improving phosphorous removal. Since the dissolved oxygen concentration is near zero in the effluent of the second anoxic reactor, probably deteriorating sludge settling properties, a second aerobic reactor is also employed prior to the secondary clarifier. The purpose of this second aerobic reactor is to oxygenate to prevent bulking of the sludge. The HRTs of the steps in fsB process are usually within the ranges of 0.5-1.5, 1-3, 4-12, 2-4, and 0.5-1 hours in anaerobic, the first anoxic, the first aerobic, the second anoxic, and the second aerobic reactors, respectively. The SRT of the system is usually kept between 10 and 20 days. Advantages of fsB process include good settling characteristics of sludge and its very high nitrogen removal efficiencies, whereas very large reactor volumes can be listed as the major disadvantage [19]. Bashar et al [20] reported removal efficiencies of 94%, 99.5%, 99.8%, and 83.5%, respectively for COD, total suspended solids (TSS), NH_3-N, TP. Another recent study on fsB process was conducted by Manav Demir et al [21] in which a modified fsB process was used for the treatment of municipal wastewaters. Results of the study indicated that removal efficiencies at levels of 87%, 82%, 93%, 89%, 88%, and 94% can be obtained respectively for COD, TN, NH_3-N, TP, PO_4^{3-}-P, and TSS. Ashrafi et al [1], on the other hand, reported a hybrid fsB and moving bed biofilm reactor (MBBR) with TN a nd TP removal efficiencies up to 95.2% and 98.3%, respectively.

The UCT process is very similar to the A²O process in that the same number of reactors are employed to achieve both nitrogen and phosphorous removal. The main difference from the A²O process comes from the paths of recycle lines. In the standard UCT process, the RAS is directed to the anoxic reactor rather than the anaerobic reactor [22] in order to reduce nitrite and nitrate load to the anaerobic reactor for improved phosphorous removal [23]. Another internal recycle is added to the system to recycle mixed liquor from anoxic to the anaerobic reactor. The UCT process can provide satisfactorily high removal efficiencies as reported by Di Trapani et al [24] who obtained up to 92% COD removal and 55% TN removal in a UCT-membrane bioreactor operated with residential wastewater. In the modified version of UCT process, on the other hand, a multi-stage anoxic reactor is employed to improve denitrification capacity. In the modified UCT process, the nitrate recycle is directed to the later sections of the anoxic reactor, while mixed liquor recycle is taken from the earlier stages. The HRTs of the UCT processes are usually within the ranges of 1-2, 2-4, and 4-12 hours in anaerobic, anoxic, and aerobic reactors, respectively [25]. The SRT is usually kept between 10 and 25 days. The advantages of UCT processes are reported as reduced nitrate loading to the anaerobic reactor that results in improved phosphorous removal for weaker wastewaters, good settling sludge, and high nitrogen removal efficiencies whereas increased cost of operation by the additional recycle stream is a major disadvantage. Li et al [26] reported effluent TN and TP concentrations as low as 8 mg/L and 0.1 mg/L, respectively in a process (bi-bio-selector for nitrogen and phosphorous removal) similar to modified UCT process. In another study, Zeng et al [27] reported the use of modified UCT process operated with 100% RAS, 300% nitrate recycle (IR), and 120% mixed liquor recycle ratios, at which COD, TN and NH_3-N removal efficiencies were reported to be 80%, 40%, and 70%, respectively.

Characteristics of influent wastewater as well as objectives of treatment are the main factors that affect selection of an activated sludge process [28]. The selection process can be easy for wastewaters of residential origin since characteristics of residential wastewaters are more or less the same in many places. However, the characteristics of municipal wastewaters depends on many factors including, but not limited to, the type and density of commercial and industrial activities, and the degree to which commercial/industrial wastewaters are mixed with residential wastewaters since these wastewaters of various origins contain various nitrogen and phosphorous contents. Therefore, a generalization for the selection of activated sludge process is not available to the knowledge of the author.

Most of the textbooks related with the topic involves detailed discussions in regard to the features and capabilities of the biological wastewater treatment processes. Although discussions include investment and operating costs of the process, the evaluations are usually made separately and performance comparisons of the processes with the same or comparable costs are usually omitted. The motivation of this study comes from the need to make evaluations on the performances of several biological wastewater treatment processes that are based on the same investment and operating costs, i.e. similar hydraulic retention times (investment cost) and similar recycle flowrates (operating costs). The aim of this study is to evaluate the performances of several activated sludge processes with comparable investment and operating costs for biological nitrogen and phosphorous removal. The performance indicators are selected as removal efficiencies for chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), total nitrogen (TN), total phosphorous (TP), and total suspended solids (TSS). Simulations of A²O, fsB, UCT, and modified UCT processes were performed at various C:N:P ratios in primary effluent with TKN/COD ratios between 0.05 and 0.15 and TP/COD ratios between 0.01 and 0.02. An MS Excel VBA based tool for wastewater treatment plant simulation based on activated sludge model no. 3 (ASM3) extended with biological phosphorous removal processes was used to obtain steady-state effluent concentrations and performances of activated sludge processes were compared.

2. MATERIALS AND METHODS

2.1. Process Configurations

Four processes, namely A^2O, fsB, standard UCT, and modified UCT processes, are compared for their COD, TN, TP, and TSS removal efficiencies. The process flow diagrams are shown in Fig. 1. For all processes, the influent (primary effluent) flowrate was 1000 m^3/h, RAS ratio was 100%, and nitrate recycle ratio was 300%. For UCT processes, the mixed liquor recycle ratio was 200%. Also, the system's SRT was kept constant at around 20 days in all simulations of all processes by adjusting waste activated sludge (WAS) flowrate. The total HRT of all process configurations was selected to be equal to 10 hours, excluding the secondary clarifier, in order to make a fair assessment of investment costs versus treatment performance. The wastewater depth in all reactors was 5 m. The dissolved oxygen concentration was kept constant at 2 g/m^3 in all aerated reactors. Volumes of reactors in each process are shown in Table 1. The surface loading of the secondary clarifier was 1 $m^3/m^2.h$ and the sidewall depth of the settler was 3.5 m for all simulations.

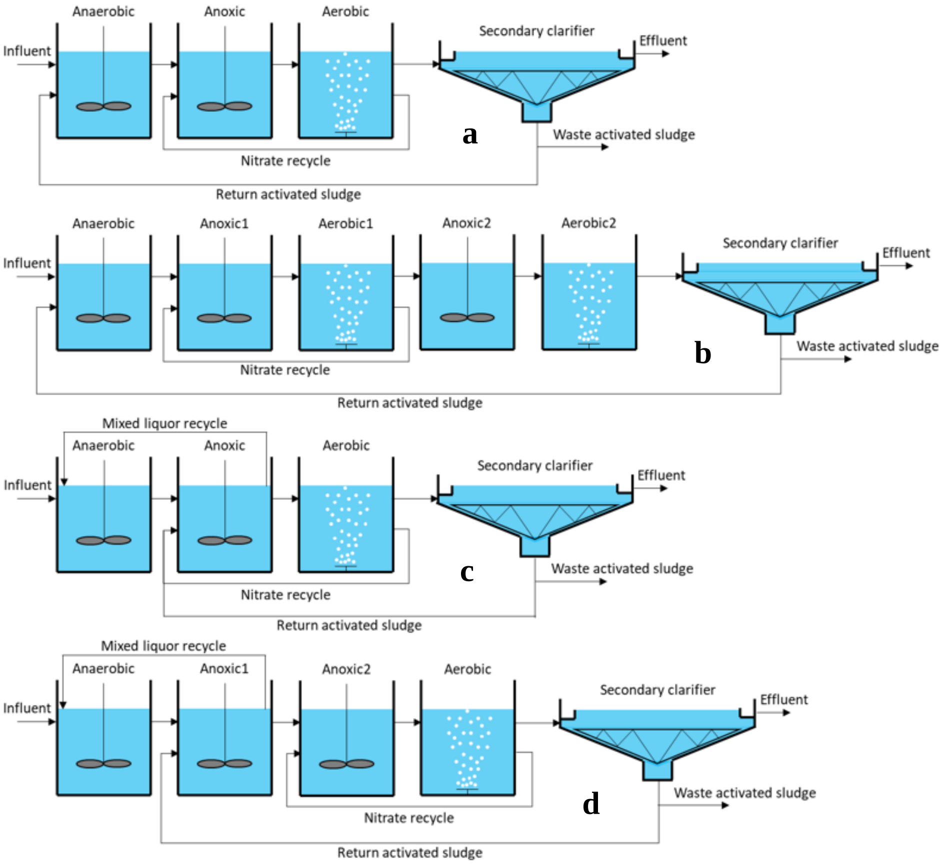

Figure 1. Mainstream flow diagram of **a.** A^2O process, **b.** fsB process, **c.** standard UCT process, and **d.** modified UCT process

Table 1. Volumes of reactors in each process

Process	Volumes (m³)					Recycle ratios
	Anaerobic	Anoxic1	Anoxic2	Aerobic1	Aerobic2	
A²O	1000	1000	–	8000	–	RAS: 100% Nitrate: 300%
fsB	1000	1000	3000	4500	500	RAS: 100% Nitrate: 300%
Standard UCT	1000	4000	–	5000	–	RAS: 100% Nitrate: 300% Mixed liquor: 200%
Modified UCT	1000	1000	3000	5000	–	RAS: 100% Nitrate: 300% Mixed liquor: 200%

2.2. Simulation Tool

An MS Excel VBA tool for wastewater treatment plant simulation, which was previously implemented for another purpose, was used for all simulations. The tool is based on activated sludge model no. 3 by Gujer et al [29] extended with the EAWAG bio-P module for biological phosphorous removal processes by Rieger et al [30], corrected/verified version of which was published later by Hauduc et al [31]. The tool is capable of steady-state and dynamic simulations of a given activated sludge process with aerated and non-aerated reactor configurations. It employs a one-dimensional, ten-layered approach for modeling the secondary clarifier with Takacs' double exponential model for settling velocity of sludge. For all simulations, default values were used for all stoichiometric and kinetic parameters [31] as well as all settling parameters [32].

2.3. Wastewater Characterization

Simulations were performed with four different activated sludge process configurations for comparing their steady-state COD, TN, TP, and TSS removal efficiencies. Considering the possibility of the process configurations being more effective for various wastewater characteristics, simulations were performed with various C:N:P ratios in primary effluent for each process. For this purpose, steady-state simulation results were obtained for TKN/COD ratios between 0.05 and 0.15 and for TP/COD ratios between 0.01 and 0.02. A total of nine different influent (primary effluent) wastewater characterization was used for each process with influent COD of 400 g/m³. Nitrite- and nitrate-nitrogen concentrations in influent wastewater were assumed to be zero. Thus, TKN and TN concentrations in influent wastewaters were equal to each other. Soluble and particulate fractions of all model components were selected based on the primary settled wastewater characteristics reported in Rössle and Pretorius [33]. Wastewater temperature was assumed as 20°C in all simulations.

3. RESULTS AND DISCUSSION

Simulations were performed for predicting COD, TN, TP, and TSS removal efficiencies in A²O, five-stage Bardenpho (fsB), standard UCT (sUCT), and modified UCT (mUCT) processes with influent TKN/COD and TP/COD ratios ranging from 0.05 to 0.15, and 0.01 to 0.02, respectively. COD, TN, TP, and TSS removal efficiencies under steady-state conditions were calculated between 85.9% and 89.6%, 64.0% and 89.8%, 12.6% and 92.8%, and 87.7% and 93.6%.

Turkish Regulation on Urban Wastewater Treatment sets the discharge limits for municipal wastewater treatment plants. The treatment plant effluents must meet the discharge limits of 125 mg/L of COD, 15 mg/L of TN, 2 mg/L of TP, and 60 mg/L of TSS. A comparison of the effluent concentrations from all of the processes for all influent wastewater characteristics with the discharge limits is provided in Table 2. In the table, effluent concentrations that exceed the related discharge limit are shown in red. For low nitrogen content (low TKN/COD ratio) in influent wastewater, all of the processes met the discharge limits except that effluent TP concentrations from A^{2}O, standard UCT, and modified UCT processes exceeded the discharge limit at high phosphorous content (high TP/COD ratio) in influent. The effluent concentrations from fsB process were always under the discharge limits. For medium nitrogen content in influent wastewater, all of the processes met the discharge limits with the exception of A^{2}O process being unable to meet the discharge limit for TP at medium-to-high phosphorous content in influent wastewater. The standard UCT process showed the best performance for high nitrogen content in influent wastewater although it failed to meet the discharge limit for TP at high phosphorous content. The A^{2}O process showed the weakest nitrogen and phosphorus removal capacity at high TKN/COD ratio, while fsB process failed in terms of TP removal at medium-to-high TP/COD ratios. Effluent TN concentrations from the modified UCT process was higher than the discharge limit.

Table 2. Effluent concentrations from all processes

Treatment process	**Pollutant parameters**	**Discharge limit (mg/L)**	**Effluent concentrations (mg/L)**								
			Low nitrogen			Medium nitrogen			High nitrogen		
			Low phosphorous	Medium phosphorous	High phosphorous	Low phosphorous	Medium phosphorous	High phosphorous	Low phosphorous	Medium phosphorous	High phosphorous
A^{2}O process	COD	125	42	42	42	42	42	42	43	43	43
	TN	15	3.65	3.76	3.78	10.8	11.0	11.0	21.6	21.6	21.6
	TP	2	0.83	1.40	2.80	1.50	3.33	5.30	2.99	5.02	6.99
	TSS	60	13	13	13	12	12	12	12	12	12
fsB process	COD	125	43	43	43	43	42	42	43	42	42
	TN	15	2.04	2.07	2.13	3.02	3.25	3.24	11.8	11.8	11.8
	TP	2	0.70	1.02	1.55	0.58	0.86	1.69	1.12	3.01	4.98
	TSS	60	13	14	14	13	13	14	13	13	13
sUCT process	COD	125	43	43	56	43	43	43	43	43	42
	TN	15	3.50	3.50	3.57	7.82	7.92	7.95	13.4	13.8	13.8
	TP	2	0.71	1.00	3.57	0.72	1.05	1.53	0.85	1.85	3.62
	TSS	60	14	14	22	13	14	14	13	13	13
mUCT process	COD	125	44	44	56	44	43	43	43	43	42
	TN	15	3.55	3.54	3.79	8.46	8.62	8.72	17.5	18.1	18.4
	TP	2	0.70	1.00	3.54	0.70	1.01	1.42	0.71	1.09	1.84
	TSS	60	14	14	22.6	13	14	14	13	14	14

In terms of steady-state COD removal efficiency, the performances of all processes were comparable to each other. Average COD removal efficiency for all processes at all C:N:P ratios was calculated as 89.1%±0.8%. Steady-state COD removal efficiencies of processes are shown in

Fig. 2. For all processes, steady-state COD removal efficiencies were satisfactorily high at all C:N:P ratios. For low TKN/COD and high TP/COD ratios (C:N:P = 100:5:2.0), however, a slight reduction in COD removal efficiency was observed in standard and modified UCT processes.

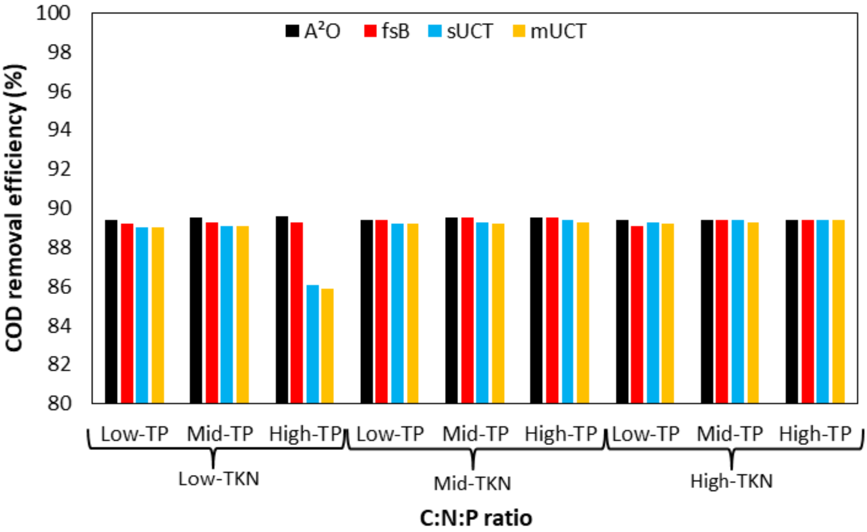

Figure 2. Steady-state COD removal efficiencies of all processes at all C:N:P ratios

Steady-state TN removal efficiencies of processes are shown in Fig. 3. In terms of TN removal efficiency, the performances of all processes were strongly correlated with influent TKN/COD ratio. The effect of increasing influent TP/COD ratio at constant TKN/COD ratio was negligible for all processes. Steady-state TN removal efficiencies ranged from 64.0% to 89.8% with an average value of 78.5%±6.7% at all C:N:P ratios. There was a clear tendency of reduction in TN removal efficiency with increasing TKN/COD ratio in the influent. The highest removal efficiencies (above 80%) were observed at low TKN/COD ratios (at a value of 0.05), while the lowest removal efficiencies were as low as 64.0% (in A²O process) at the highest TKN/COD ratio (at a value of 0.15). The A²O process was the least effective process in terms of TN removal at all C:N:P ratios. Although standard and modified UCT processes showed similar TN removal efficiencies for low TKN/COD ratios, the discrepancy between TN removal performances of these processes increased gradually with increasing TKN/COD ratio in the influent. At the highest TKN/COD ratio, TN removal efficiencies for the standard and modified UCT processes were around 77% and 70%, respectively. At all C:N:P ratios, fsB process showed the best performance in terms of TN removal. The steady-state TN removal efficiency in fsB process was around 90% at the lowest TKN/COD ratio with the lowest value dropping down to 80% at the highest TKN/COD ratio in the influent. One can conclude that, for the main objective of nitrogen removal, fsB process can be employed no matter the influent C:N:P ratio.

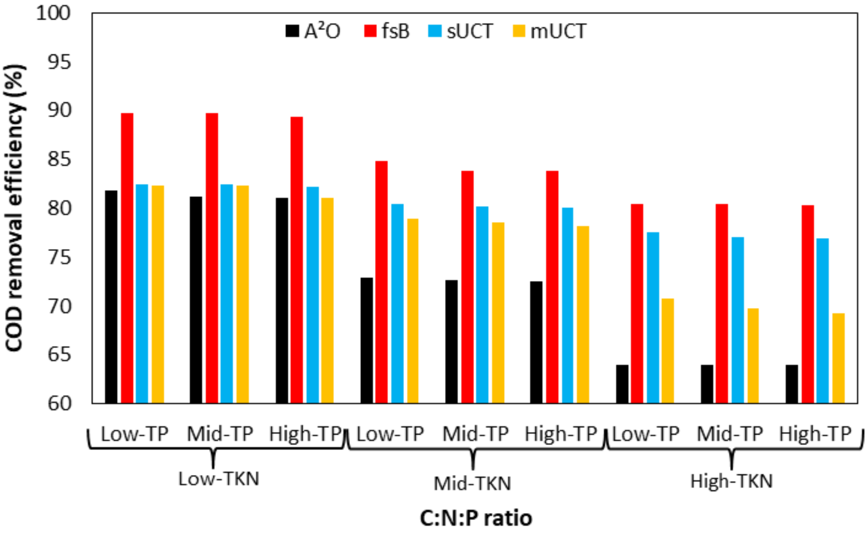

Figure 3. Steady-state TN removal efficiencies of all processes at all C:N:P ratios

Steady-state TP removal efficiencies of processes are shown in Fig. 4. Although negligible at low TKN and low TP, both TKN/COD and TP/COD ratios in the influent affected TP removal efficiencies in all process. Influent TKN/COD ratio was more effective in determining TP removal efficiency than influent TP/COD ratio. TP removal efficiencies were around 80% in all processes at low TKN and low-to-mid TP in the influent. However, sudden reductions in TP removal efficiency were observed when influent TP/COD ratio was raised to 0.02 at low influent TKN. The highest TP removal efficiencies were observed for fsB at mid-TKN influent. In contrast, the performance of A^2O process, in terms of TP removal, was the lowest at almost all C:N:P ratios. TP removal efficiency in A^2O process dropped to as low as 12.6% at high TKN and high TP in the influent. At C:N:P ratio of 100:10:2.0, TP removal efficiencies of fsB, sUCT, and mUCT processes were comparable with those of sUCT and mUCT processes being slightly higher than fsB. Considering the fact that sUCT and mUCT processes require an additional recycle line (Fig. 1), fsB process can still be considered to be more cost-effective in this case. Standard and modified UCT processes (sUCT and mUCT) were the best selection in terms of TP removal performance at high TKN/COD ratios in the influent. Of these two processes, the balance shifted gradually in favor of modified UCT process with increasing TP/COD ratio in the influent. One can conclude that, for the objective of TP removal, fsB process is the best alternative at low-to-mid TKN/COD ratios in the influent, while modified UCT process can be the best at high influent TKN/COD ratios.

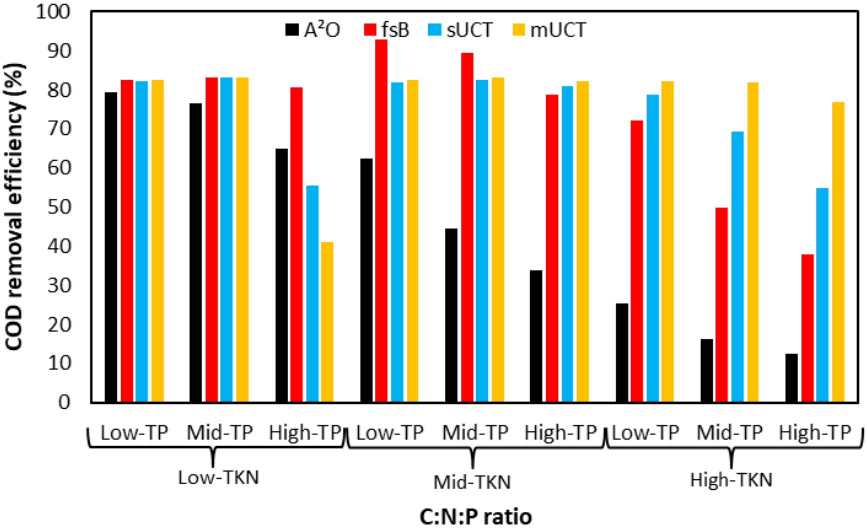

Figure 4. Steady-state TP removal efficiencies of all processes at all C:N:P ratios

Steady-state TSS removal efficiencies of processes are shown in Fig. 5. TSS removal efficiency is a criterion to evaluate the performance of secondary clarifier rather than process configurations. Nevertheless, it is related with the production of mixed liquor suspended solids in the process reactors. For all processes, TSS removal efficiencies were comparable, except for the standard and modified UCT processes at low TKN and high TP in the influent. At all C:N:P ratios, TSS removal efficiencies were satisfactory.

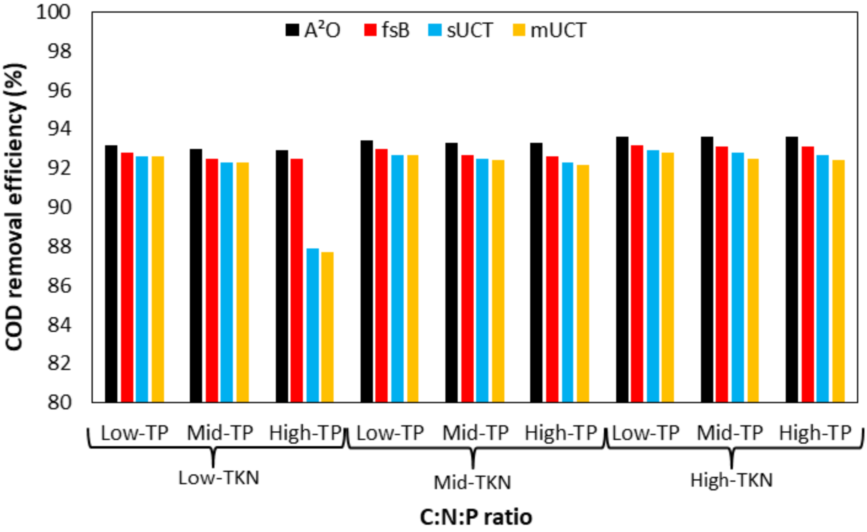

Figure 5. Steady-state TSS removal efficiencies of all processes at all C:N:P ratios

Steady-state concentrations of soluble components of concern (NO_2-N+NO_3-N, and PO_4-P) in process reactors with respect to hydraulic retention time are shown in Fig. 6. The values were obtained at an influent C:N:P ratio of 100:10:1.5. Nitrogen and phosphorous components in particulate form such as organic nitrogen and polyphosphates are not shown in Fig. 6 since the concentrations of particulate components reach up to 5000 mg/L in process reactors.

The concentrations at the end of total hydraulic retention time (10 h) can be assumed as the effluent concentrations for these components since the biochemical reactions in secondary clarifier is neglected and these components are in soluble form. The highest effluent NO_3-N concentration was observed in A^2O process as 9.5 mg/L. A very small fraction of this was reduced in anoxic reactor, which suggested a smaller TN removal efficiency in A^2O process. On the other hand, the highest NO_3-N concentration in fsB process was observed in the effluent of the first aerobic reactor, suggesting that nitrification process takes place mainly in the first aerobic reactor in fsB process. NO_3-N concentration at the end of 5 hours in modified UCT process was slightly higher than standard UCT process. The denitrification capacity of the standard UCT process was higher. As a result, effluent NO_3-N concentration from standard UCT process was lower.

Steady-state PO_4-P concentrations at the end of 1 hour (anaerobic effluent) was drastically higher than effluent concentrations in all processes (Fig. 6), suggesting that anaerobic hydrolysis processes were effective. The lowest PO_4-P concentration in anaerobic effluent was observed in A^2O process, for which the TP removal efficiency was also the lowest. For all processes, most of phosphorous uptake took place under anoxic conditions. For fsB process, approximately 60% of PO_4-P in anaerobic effluent was removed in the first anoxic reactor. The highest PO_4-P concentration in anaerobic effluent was observed in modified UCT process. The reason for this is that return activated sludge is recycled to the first anoxic reactor and mixed liquor is recycled from the effluent of the first anoxic reactor to anaerobic reactor. Fig. 6 clearly shows the positive effect of recycling return activated sludge to the anoxic reactor rather than directly to the anaerobic reactor. This configuration is beneficial for phosphorous removal in wastewater treatment plants.

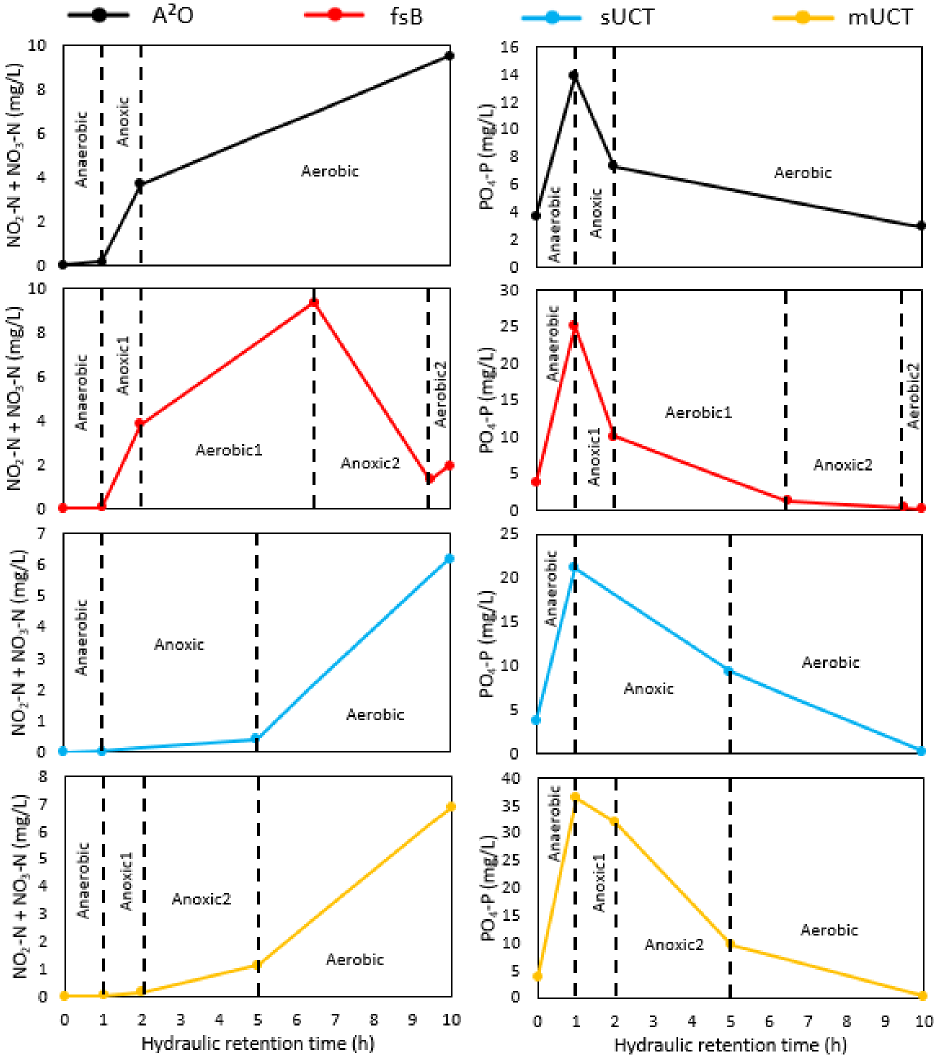

Figure 6. Steady-state NO$_2$-N+NO$_3$-N (left) and PO$_4$-P (right) concentrations in process reactors at an influent C:N:P of 100:10:1.5 with respect to hydraulic retention time.

4. CONCLUSIONS

Simulations were performed to obtain COD, TN, TP, and TSS removal efficiencies of A^2O, five-stage Bardenpho (fsB), standard UCT, and modified UCT processes for biological nutrient removal from wastewaters using an MS Excel wastewater treatment plant simulation tool based on Activated Sludge Model No. 3 extended with biological phosphorous removal processes. Total hydraulic retention times (HRTs) of the processes were 10 hours with the same sludge retention times (SRTs) of 20 days, which was set by adjusting waste activated sludge flowrate. Simulations were performed with various influent C:N:P ratios. Three different influent TKN/COD ratios (also equal to TN/COD ratio) between 0.05 and 0.15, and three different influent TP/COD ratios between 0.01 and 0.02 were used for simulations and each process configuration were simulated with 9 different influent wastewater characteristics. Influent wastewater COD was assumed as 400 mg/L in each simulation. Evaluations were based on steady-state removal efficiencies of each process configuration for COD, TN, TP, and TSS.

All processes showed satisfactory performance in terms of COD removal no matter the influent C:N:P ratio. Steady-state COD removal efficiencies were calculated between 85.9% and 89.6%, with an average value of 89.1±0.8%. None of the processes showed distinguishing performance to another in terms of COD removal. Increasing TKN/COD ratio in the influent resulted in a clear reduction in TN removal efficiency for all processes, while influent TP/COD ratio was less effective. At the same HRT and the same SRT, fsB process, with the highest TN removal efficiencies between 80.3% and 89.9%, was more resistant to high TKN and TP loads compared to other processes. In terms of phosphorous removal, performances of all processes were comparable to each other at low influent TKN/COD and low-to-mid TP/COD ratios with an average removal efficiency of 81.6%. However, TP removal efficiency of standard and modified UCT processes dropped considerably at low TKN, high TP loads. On the other hand, standard and modified UCT processes showed the highest TP removal efficiencies at high TKN loads to the system. Following conclusions can be withdrawn from the results of this study:

- Considering the fact that characterization of municipal wastewaters in terms of C:N:P ratio is a function of the density of commercial/industrial activities and the degree to which commercial/industrial wastewaters are mixed with wastewaters of residential origin, selection of the biological treatment process for municipal wastewaters must be based on influent C:N:P ratio.
- With the primary objective of treatment as nitrogen removal, fsB process can provide higher removal efficiencies at the same HRT and SRT compared to other processes. This is valid for all influent C:N:P ratios. Thus, fsB process is the most economical alternative to process selection.
- With the primary objective of treatment as phosphorous removal, fsB can be more advantageous for low-to-mid influent TKN/COD ratios in terms of investment and operating costs. For high influent TKN/COD ratios, performance of modified UCT process is far better than others. One must note that the UCT processes require an additional recycle line to recycle mixed liquor from anoxic to anaerobic reactor.
- For both nitrogen and phosphorous removal, on the other hand, fsB process offers the most economical solution at low-to-mid influent TKN/COD ratios with the highest removal efficiencies per unit HRT. For high TKN/COD ratio in the influent, however, standard UCT process can be the best selection in terms of treatment performance.

ABBREVIATIONS

UCT, University of Cape Town, **COD**, chemical oxygen demand, **TKN**, Total Kjeldahl nitrogen, **TN**, total nitrogen, **TP**, total phosphorous, **BNR**, biological nutrient removal, **VIP**, Virginia Initiative Plant, **sUCT**, standard UCT, **mUCT**, modified UCT, **fsB**, five-stage Bardenpho, **RAS**, return activated sludge ratios, **NO_2^--N**, nitrite nitrogen, **NO_3^--N**, nitrate nitrogen, **N_2**, nitrogen gas, **PAOs**, phosphorous accumulating organisms, **PO_4^{3-}-P**, phosphate-phosphorous, **NH_3-N**, ammonia nitrogen, **HRT**, hydraulic retention times, **SRT**, sludge retention times, **TP**, total phosphorous, **TSS**, total suspended solids, **ASM3**, activated sludge model no. 3, **WAS**, waste activated sludge flowrate.

REFERENCES

[1] Ashrafi E., Zeinabad A.M., Borghei S.M., Torresi E., Sierra J.M., "Optimising nutrient removal of a hybrid five-stage Bardenpho and moving bed biofilm reactor process using response surface methodology", J Environ Chem Eng, 7, 102861, 2019.

[2] Shen Y., Gao J., Li L., "Municipal wastewater treatment via co-immobilized microalgal-bacterial symbiosis: Microorganism growth and nutrients removal", Bioresource Technol, 243, 905–913, 2017.

[3] Wang D., Tooker N.B., Srinivasan V., Li G., Fernandez L.A., Schauer P., Menniti A., Maher C., Bott C.B., Dombrowski P., Barnard J.L., Onnis-Hayden A., Gu A.Z., "Side-stream enhanced biological phosphorus removal (S2EBPR) process improves system performance - A full-scale comparative study", Water Res, 167, 115109, 2019.

[4] Han Y., Yang K., Yang T., Zhang M., Li L., "Bioaerosols emission and exposure risk of a wastewater treatment plant with A2O treatment process", Ecotox Environ Safe, 169, 161-168, 2019.

[5] Azhdarpoor A., Abbasi L., Samaei M.R., "Investigation of a new double-stage aerobic-anoxic continuous-flow cyclic baffled bioreactor efficiency for wastewater nutrient removal", J Environ Manage, 211, 1-8, 2018.

[6] Bashar R., Gungor K., Karthikeyan K.G., Barak P., "Cost effectiveness of phosphorus removal processes in municipal wastewater treatment", Chemosphere, 197, 280-290, 2018.

[7] Diez-Montero R., De Florio L., Gonzalez-Viar M., Herrero M., Tejero I., "Performance evaluation of a novel anaerobic–anoxic sludge blanket reactor for biological nutrient removal treating municipal wastewater", Bioresource Technol, 209, 195–204, 2016.

[8] Li S., Fei X., Chi Y., Jiao X., Wang L., Integrated temperature and DO effect on the lab scale A2O process: Performance, kinetics and microbial community", Int Biodeter Biodegr, 133, 170-179, 2018.

[9] Czerwionka K., Makinia J., Pagilla K.R., Stensel H.D., "Characteristics and fate of organic nitrogen in municipal biological nutrient removal wastewater treatment plants", Water Res, 46, 2057-2066, 2012.

[10] Islam M.S., Zhang Y., Dong S., McPhedran K.N., Rashed E.M., El-Shafei M.M., Noureldin A.M., El-Din M.G., "Dynamics of microbial community structure and nutrient removal from an innovative side-stream enhanced biological phosphorus removal process", J Environ Manage, 198, 300-307, 2017.

[11] Fang F., Qiao L.L., Cao J.S., Li Y., Xie W.M., Sheng G.P., Yu H.Q., "Quantitative evaluation of A2O and reversed A2O processes for biological municipal wastewater treatment using a projection pursuit method", Sep Purif Technol, 166, 164–170, 2016.

[12] Gallardo-Altamirano M.J., Maza-Marquez P., Pena-Herrera J.M., Rodelas B., Osorio F., Pozo C., "Removal of anti-inflammatory/analgesic pharmaceuticals from urban wastewater in a pilot-scale A2O system: Linking performance and microbial population dynamics to operating variables", Sci Total Environ, 643, 1481–1492, 2018.

[13] Ravishankar A., Moazzem S., Jegatheesan V., "Performance evaluation of A2O MBR system with graphene oxide (GO)blended polysulfone (PSf) composite membrane for treatment of high strength synthetic wastewater containing lead", Chemosphere, 234, 148-161, 2019.

[14] Rollemberg S.L.S., Barros A.N., Lira V.N.S.A., Firmino P.I.M., Santos A.B., "Comparison of the dynamics, biokinetics and microbial diversity between activated sludge flocs and aerobic granular sludge", Bioresource Technol, 294, 122106, 2019.

[15] Ye C., Zhou Z., Li M., Liu Q., Xu T., Li J., "Evaluation of simultaneous organic matters and nutrients removal from municipal wastewater using a novel bioreactor (D-A2O) system", J Environ Manage, 218, 509-515, 2018.

[16] Rong Y., Liu X., Wen L., Jin X., Shi X., Jin P., "Advanced nutrient removal in a continuous A^2/O process based on partial nitrification-anammox and denitrifying phosphorus removal", J Water Process Eng, 36, 101245, 2020.

[17] Zong Y.C., Hao K.Y., Li Y.W., Lu G.H., Huang D.C., "Nitrogen and phosphorous removal of pilot-scale anaerobic-anoxic-aerobic process under plateau environmental factors", Appl Ecol Environ Res, 17(5), 12213-12226, 2019.

[18] Emara M.M., Ahmed F.A., Abdel-Aziz F., Abdel-Razek A., "Biological Nutrient Removal in Bardenpho Process", Journal of American Science, 10, 1-9, 2014.

[19] Banayan Esfahani E., Asadi Zeidabadi F., Bazargan A., McKay G., "The Modified Bardenpho Process", Springer International Publishing AG 2018, C. M. Hussain (ed.), Handbook of Environmental Materials Management, https://doi.org/10.1007/978-3-319-58538-3_87-1

[20] Bashar R., Gungor K., Karthikeyan K.G., Barak P., "Cost effectiveness of phosphorus removal processes in municipal wastewater treatment", Chemosphere, 197, 280-290, 2018.

[21] Manav Demir N., Yildirim A., Coskun T., Balcik Canpolat C., Debik E., "Carbon and nutrient removal from domestic wastewaters in a modified 5-stage Bardenpho process via fuzzy modeling approach", Environ Prot Eng, 45(1), 5-16, 2019.

[22] Ruzhitskaya O., Gogina E., "Methods for Removing of Phosphates from Wastewater", MATEC Web of Conferences., 106, 07006, 2017.

[23] Vaiopoulou E., Aivasidis A., "A modified UCT method for biological nutrient removal: Configuration and performance", Chemosphere, 72, 1062–1068, 2008.

[24] Di Trapani D., Capodici M., Cosenza A., Di Bella G., Mannina G., Torregrossa M., Viviani G., "Evaluation of biomass activity and wastewater characterization in a UCT-MBR pilot plant by means of respirometric techniques", Desalination, 269, 190-197, 2011.

[25] Tchobanoglous G., Burton F.L., Stensel H.D., "Wastewater Engineering Treatment and Reuse", Metcalf and Eddy, McGraw-Hill Inc., New York, 2003.

[26] Li D., Li W., Zhang K., Zhang G., Zhang H., Zhang D., Lv P., Wu J., "Nutrient removal by full-scale Bi-Bio-Selector for nitrogen and phosphorus removal process treating urban domestic sewage at low C/N ratio and low temperature conditions", Process Saf Environ, 140, 199-210, 2020.

[27] Zeng W., Wang X., Li B., Bai X., Peng Y., "Nitritation and denitrifying phosphorus removal via nitrite pathway from domestic wastewater in a continuous MUCT process", Bioresour Technol, 143, 187-195, 2013.

[28] Zhang Y., Zhang C., Qiu Y., Li B., Pang H., Xue Y., Liu Y., Yuan Z., Huang X., "Wastewater treatment technology selection under various influent conditions and effluent standards based on life cycle assessment", Resources, Conservation & Recycling, 154, 104562, 2020.

[29] Gujer W., Henze M., Mino T., van Loosdrecht M., "Activated sludge model no. 3", Water Sci Technol, 39, 183-193, 1999.

[30] Rieger L., Koch G., Kühni M., Gujer W., Siegrist H., "The eawag bio-P module for activated sludge model no. 3", Water Res, 35(16), 3887-3903, 2001.

[31] Hauduc H., Rieger L., Takacs I., Heduit A., Vonrolleghem P.A., Gillot S., "A systematic approach for model verification – Application on seven published activated sludge models", Water Sci Technol, 61, 825-839, 2010.

[32] Takacs I., Patry G.G., Nolasco D., "A dynamic model of the clarification-thickening process", Water Res, 25, 1263-1271, 1991.

[33] Rössle W.H., Pretorius W.A., "A review of characterization requirements for in-line prefermenters. Paper 1: Wastewater characterization", Water SA, 27(3), 405-412, 2001.