Comparisons of nitrogen and phosphorus removal efficiency in A²/O process, UCT process, MUCT process, enhanced phosphorus removal process and inverted A²/O process based on GPS-X simulation

Shuhan Lei¹,², Jianqiang Zhao¹,²,⁴, Shuting Xie¹,², Junkai Zhao¹,², Jia Min³, Xiaoqing Ma¹,² and Chunxiao Yan¹,²

¹School of Water and Environment, Chang’an University, Xi’an 710064, Shaanxi, China
²Key Laboratory of Subsurface Hydrology and Ecological Effect in Arid Region of Ministry of Education, Xi’an 710064, Shaanxi, China
³China Electronic Research Institute of Engineering Investigations and Design, Xi’an 710054, Shaanxi, China
⁴E-mail: 626710287@qq.com

Abstract. By using the GPS-X software, the enhanced phosphorus removal (EPR) process was simulated in this study. The comparisons among nitrogen and phosphorus removal efficiency of traditional A²/O process, University of Cape Town (UCT) process, Modified University of Cape Town (MUC) process and inverted A²/O process were conducted, in order to determine the best process under the same conditions of construction investment and running cost. The results showed that the simply reversed A²/O process exhibited poor total phosphorus (TP) removal efficiency under low carbon level. The effluent water qualities of the other three processes under low, medium and high levels of carbon source met the first B level criteria (GB18918-2002) for China. The ranges of removal efficiencies of TP, TN, NH₄⁺-N and COD were 63.15% ~ 94.91%, 55.38% ~ 77.89%, 96.91% ~ 97.70% and 90.89% ~ 93.66%, respectively. Denitrifying phosphorus removal occurred in anoxic tank of EPR process. The phosphorus accumulation concentration was 6.91 mg/L, and the maximum phosphorus released in anaerobic tank was 24.01 mg/L, and the higher P release gave the EPR process a high P removal efficiency. Except for the TN which met the first B level criteria (GB18918-2002), TP, NH₄⁺-N and COD met the first A level criteria GB18918-2002), above that, the process was feasible. Inverted A²/O process exhibited the highest nitrogen removal efficiency for its sufficient carbon source in anoxic tank.

1. Introduction
A²/O process has the function of simultaneously removing nitrogen and phosphorus. It has been widely used in wastewater treatment plants in China [1]. However, it also has some defects, such as the low C/N ratios capable of aggravating the competition of carbon sources, and the reflux of nitrifying liquid might affect anaerobic phosphorus release. Researchers have developed numerous methods to improve the A²/O processes [2].
The requirement of wastewater treatment is increasingly strict, so it is necessary to study new wastewater treatment technologies. In this study, an enhanced phosphorus removal (EPR) process was proposed based on UCT process. Due to the low C/N ratio of UCT process, some nitrate would enter the anaerobic tank [3]. Thus, aerobic nitrification liquid reflux was removed in the UCT process to protect the anaerobic environment for phosphorus release, and strengthen the phosphorus removal. In this study, GPS-X6.4 software was used to simulate and compare the N and P removal efficiency of traditional A^2/O process, UCT process, MUCT process, EPR process and inverted A^2/O process. The process parameters and operating parameters under high, medium and low carbon source levels were controlled in the simulation, to verify the feasibility of EPR process and choose the optimal process.

GPS-X6.4 software was used in this simulation. GPS-X was a modular, multi-purpose simulation tool developed by Hydromantis Environmental Consulting, Canada [4]. The mechanism models include all activated sludge mathematical models launched by IWA, such as ASM 1 and ASM 3 models for carbon and nitrogen removal and ASM 2D model for nitrogen and phosphorus removal, as well as Mantis and Newgenerate models developed by the IWA. GPS-X software can simulate a variety of sewage treatment processes, including SBR, biological aerated filter, oxidation ditch and other processes, according to the needs of the designer can establish a variety of treatment processes and simulation.

2. Materials and methods

2.1. Simulation process

The five wastewater treatment processes selected in this comparison were A^2/O process, UCT process, MUCT process, EPR process and inverted A^2/O process. The flow chart of the five sewage treatment processes was shown in Figure 1.

**Figure 1.** Five process flow charts.
2.2. The water quality
In this study, influent water quality was used as the first phase of a wastewater treatment plant (WWTP) in Xi’an. The scale was $1.2 \times 10^4$ m$^3$/d. Influent water qualities of the WWTP were shown in Table 1. The temperature and alkalinity were set as 20°C and 350 mg CaCO$_3$/L, respectively.

| Index | COD(Cr) mg/L | BOD$_5$ mg/L | SS mg/L | NH$_4$-N mg/L | TKN mg/L | TN mg/L | TP mg/L | pH | BOD$_5$/TN | BOD$_5$/COD |
|-------|--------------|--------------|---------|---------------|-----------|---------|---------|----|-------------|-------------|
| Concentration | 380 | 190 | 260 | 34 | 45 | 45 | 4.2 | 6~9 | 4.22 | 0.5 |

The influent water of the biological reaction tank should meet BOD$_5$/TN ≥4, BOD$_5$/TP ≥17 to achieve N and P removal [5, 6]. The influent BOD$_5$/TN and BOD$_5$/TP of the WWTP were 4.22 and 45.23, belonging to the level of medium carbon source. In this study, the influent quality of the WWTP and the nitrogen and phosphorus removal effects of five processes under low carbon source (BOD$_5$/TN=3.5, BOD$_5$/TP=37.5) and high carbon source (BOD$_5$/TN=5.5, BOD$_5$/TP=58.92) were simulated [2, 7].

2.3. Settlement of condition
The settlement in this study was according to some Chinese National and industrial standards: Water Supply and Drainage Design Manual, Technical Specifications for Anaerobic-Anoxic-Oxic Activated Sludge Process(HJ 576—2010), Technical specification for orperation, maintenance and safety of municipal wastewater treatment plant (CJJ 60—2011) and Code for design of outdoor wastewater engineering (GB 50014-2006), etc. The same process parameters and operating parameters were set of the five processes: The volumes were shown in Table 2, sludge reflux ratio was 100%, mixed liquid reflux ratio was 100%, aeration tank DO was 2 mg/L, SRT=15 d and HRT of the tanks are listed in Table 3.

| Project | Volume (h) | A$^2$/O Process | UCT Process | MUCT Process | Enhanced Phosphorus Removal Process | Inverted A$^2$/O Process |
|---------|------------|-----------------|-------------|--------------|------------------------------------|-------------------------|
| Anaerobic tank | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 |
| Anoxic tank I | 2000 | 2000 | 1000 | 2000 | 2000 |
| Anoxic tank II | / | / | 1000 | / | / |
| Aerobic tank | 5000 | 5000 | 5000 | 5000 | 5000 |
| Secondary | 1050 | 1050 | | | |
| Sedimentation tank | (350m$^3$×3m) | (350m$^3$×3m) | (350m$^3$×3m) | (350m$^3$×3m) | (350m$^3$×3m) |

Table 3. The HRT of different process.

| HRT | A$^2$/O Process (h) | UCT Process (h) | MUCT Process (h) | Enhanced Phosphorus Removal Process (h) | Inverted A$^2$/O Process (h) |
|-----|---------------------|-----------------|-----------------|----------------------------------------|-----------------------------|
| Biochemical system | 18.1 | 18.1 | 18.1 | 18.1 | 18.1 |
| Anaerobic tank | 2 | 2 | 2 | 2 | 2 |
| Anoxic tank I | 4 | 4 | 2 | 4 | 4 |
| Anoxic tank II | / | / | 2 | / | / |
| Aerobic tank | 10 | 10 | 10 | 10 | 10 |
| Secondary sedimentation tank | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 |

2.4. Simulation method
This simulation selected the corresponding mathematical model for each unit: the influent quality was codstates model based on COD component; each reaction tank was of ASM2d model with
synchronous nitrogen and phosphorus removal; and the secondary sedimentation tank was of simple 1d model.

The influent quality index was modified in this simulation, and the parameters in the model library were adjusted according to the influent quality index, such as fbod (BOD$_5$/BOD$_U$ value) adjusted to 0.6097, frsp (soluble phosphorus orthophosphate ratio) adjusted to 1.0, etc.

Finally entered the simulation interface, established the model, ran the simulation in a steady state environment for 60 days, and output the running results.

3. Result and discussion

3.1. Comparison of carbon, nitrogen and phosphorus removal efficiency

The effluent TP, TN, NH$_4^+$-N and COD of the five processes were shown in Figure 2.

![Effluent TP, TN, NH$_4^+$-N and COD of the five processes under low, medium and high carbon level.](image)

In the case of three carbon levels, the effluent quality of all processes met the first B level criteria, Discharge Standard of Pollutants for Municipal Wastewater Plan (GB18918-2002) for China [8], except for inverted A$^2$/O process under the condition of low carbon sources. The removal efficiencies of TP, TN, NH$_4^+$-N and COD by the five processes were (63.15% ~ 94.91%), (55.38% ~ 77.89%), (96.91% ~ 97.70%) and (90.89% ~ 93.66%), respectively. Under the high, medium and low carbon
source levels, the effluent TP concentration of inverted A²/O process was higher, and the effluent TP concentration of inverted A²/O process was as high as 1.55 mg/L at the low carbon source level. The effluent TP concentration of A²/O process at low, medium and high carbon source levels were 0.55 mg/L, 0.48 mg/L, 0.35 mg/L respectively. UCT process at low, medium and high carbon source levels were 0.55 mg/L, 0.48 mg/L, 0.35 mg/L respectively. MUCT process at low, medium and high carbon source levels were 0.54 mg/L, 0.40 mg/L, 0.32 mg/L respectively. ERP process at low, medium and high carbon source levels were 0.29 mg/L, 0.27 mg/L, 0.21 mg/L respectively. The effluent TN concentration of the EPR process was higher, which was 19.98 mg/L at the high carbon source level. While the other four processes had a lower effluent TN concentration, which was 9.95~17.4 mg/L. Above that, EPR process had a strong phosphorus removal ability but a weak denitrification ability. Contrary, inverted A²/O process had a strong denitrification ability but a weak phosphorus removal ability. All effluent indexes met the first A level criteria (GB18918-2002). Except for the total nitrogen removal efficiency, which met the first B level criteria, above that, the EPR process was feasible.

3.2. Process analysis of denitrification and phosphorus removal

In order to compare the changes of PO₄³⁻-P, NO₃⁻-N and NH₄⁺-N in the five processes, the design quality of influent (medium carbon source level) of the WWTP was selected for analysis. The concentration the concentration of soluble PO₄³⁻-P, NO₃⁻-N and NH₄⁺-N in the reflux sludge was assumed equal to that in the secondary sedimentation tank. According to the model, the variation of concentration of soluble PO₄³⁻-P, NO₃⁻-N and NH₄⁺-N in five processes along the process was obtained. The results were shown in Table 4.

3.2.1. Analysis of ammonia nitrogen removal process. Except that the concentration of NH₄⁺-N in the second and first tank of inverted A²/O process changed slightly, the concentration of ammonia nitrogen in the other four processes showed a trend of gradual decrease.

3.2.2. Analysis of denitrification process. The comparison of NO₃⁻-N concentration in the effluent of each stage of the five processes showed that the effluent concentration in the anoxic tank of each process was lower than the influent concentration, indicating that denitrification had occurred in the anoxic tank. Inverted A²/O process prepositioned the anoxic tank, with sufficient denitrification carbon sources and a large amount of reflux nitrification liquid flowing back to the anoxic tank, which promoted denitrification and improved the denitrification capacity of the system [9]. The denitrification rate was 91.60%, which was higher than the other five processes. The denitrification capacity of the anaerobic tank was weak and the denitrification rate was 50.37% due to the absence of nitrification fluid reflux in the EPR process. In the MUCT process, the concentration of carbon-containing organic matter entering the second anoxic tank was lower than that entering the first anoxic tank, and the concentration of easily biodegradable carbon-containing organic matter was lower. Therefore, the denitrification rate of the second anoxic tank was lower than that of the first anoxic tank, which were 61.27% and 54.90%, respectively.

3.2.3. Analysis of anaerobic/anoxic phosphorus release process. By comparing the phosphorus release phenomenon of the anaerobic tank of the five processes, it could be seen that the phosphorus release amount of the EPR process was the largest up to 24.01 mg/L; the phosphorus release amount of inverted A²/O process was the smallest, which was 6.08mg/L; the phosphorus release amount of the other three processes are respectively: A²/O 12.99 mg/L, UCT 13.22 mg/L, MUCT 14.53 mg/L.

Compared to inverted A²/O process, the nitrification liquid in the traditional A²/O process did not flow through the anaerobic tank, so the degree of anaerobic degradation was more sufficient, and the volatile fatty acid (VFA) utilization by phosphorus accumulating bacteria was more sufficient [10]. In addition, the concentration of nitrate nitrogen in the effluent of the anaerobic tank with inverted A²/O process and the traditional A²/O process were both lower than the influent concentration, indicating that denitrification had occurred in the anaerobic tank, and phosphorus release began when the
concentration of nitrate nitrogen was close to zero. Therefore, inverted A^2/O process prepositioned the anoxic tank, and the carbon source needed by inverted phosphorous accumulation bacteria was consumed by the denitrifying bacteria, which inhibited the anaerobic phosphorus release. Therefore, the traditional A^2/O process had better phosphorus removal effect.

Table 4. Changes of soluble PO_4^{3-}-P, NO_3^-N and NH_4^+-N concentrations along the process for the five processes (Units: mg/L).

| Processes | Project | Influent quality | First tank flooded | First tank outlet | Second tank flooded | Second tank outlet | Third tank flooded | Third tank outlet | Fourth tank flooded | Fourth tank outlet |
|-----------|---------|-----------------|-------------------|------------------|-------------------|-------------------|------------------|------------------|-------------------|------------------|
| A^2/O     | PO_4^{3-}-P | 4.2             | 5.16              | 18.15            | 9.14              | 5.55              | 5.55             | 0.18             |                   |                   |
|           | NO_3^-N   | 0               | 4.82              | 0.11             | 4.88              | 2.12              | 0.52             | 9.64             |                   |                   |
|           | NH_4^+-N  | 34              | 17.49             | 18.19            | 9.58              | 9.94              | 9.94             | 0.98             |                   |                   |
| UCT       | PO_4^{3-}-P | 4.2             | 5.08              | 18.30            | 9.52              | 5.53              | 5.53             | 0.17             |                   |                   |
|           | NO_3^-N   | 0               | 0.89              | 0.03             | 5.24              | 1.33              | 1.33             | 10.45            |                   |                   |
|           | NH_4^+-N  | 34              | 17.87             | 18.68            | 9.79              | 9.81              | 9.81             | 0.91             |                   |                   |
| MUCT      | PO_4^{3-}-P | 4.2             | 5.11              | 19.64            | 10.43             | 9.31              | 5.20             | 5.06             | 0.14              |                   |
|           | NO_3^-N   | 0               | 0.07              | 0.01             | 2.84              | 1.10              | 5.72             | 2.58             | 12.27             |                   |
|           | NH_4^+-N  | 34              | 24.12             | 25.08            | 19.13             | 19.17             | 10.22            | 9.99             | 0.91              |                   |
| Enhanced  | PO_4^{3-}-P | 4.2             | 11.07             | 35.08            | 21.41             | 14.5              | 14.5             | 0.09             |                   |                   |
| Phosphorus| NO_3^-N   | 0               | 0.04              | 0.01             | 1.35              | 0.67              | 0.67             | 18.19            |                   |                   |
| Removal   | NH_4^+-N  | 34              | 24.78             | 25.77            | 19.57             | 20.17             | 20.17            | 0.97             |                   |                   |
| Process   | PO_4^{3-}-P | 4.2             | 2.37              | 3.47             | 3.47              | 9.55              | 9.55             | 0.33             |                   |                   |
| Inverted  | NO_3^-N   | 0               | 7.02              | 0.59             | 0.59              | 0.04              | 0.04             | 9.36             |                   |                   |
| A^2/O     | NH_4^+-N  | 34              | 9.23              | 9.62             | 9.62              | 9.94              | 9.94             | 0.98             |                   |                   |

Compared to the traditional A^2/O process, the UCT process relowed the sludge to the anoxic tank rather than the anaerobic tank, and increased the reflux from the anoxic tank to the anaerobic tank. The nitrate nitrogen in the reflux sludge and the reflux mixture was denitrified in the anoxic tank, preventing the nitrate in the nitrification liquid from entering the anoxic tank and preventing the nitrate from inhibiting the anaerobic phosphorus release [11].

In contrasts with UCT, MUCT added an anaerobic tank, returned sludge return to the previous anaerobic tank, mixture after return back to anoxic tank, and stick to completely separate the sludge and liquid nitrogen, thus reducing the possibility of nitrate nitrogen into anaerobic tank, phosphorous accumulating in the anaerobic tank protected from the interference of nitrate nitrogen release phosphorus, increased the removal efficiency of phosphorus [12].

Compared with UCT process, the EPR process eliminated the reflux process of nitrifying liquid and avoided the reflux of nitrifying liquid to anaerobic tank, which interfered with an aerobic phosphorus release. It could be seen from Table 4 that the concentration of nitrate nitrogen in the influent water of the anaerobic tank in the EPR process was the lowest, which inhibited the denitrification process to a great extent.

3.2.4. Analysis of denitrifying phosphorus removal process. The effluent concentration of PO_4^{3-}-P in traditional A^2/O process, UCT process, MUCT process, and EPR process were higher than that in the influent, indicating that EPR had occurred in the anoxic tank, phosphorus uptake amount were 3.59 mg/L (traditional A^2/O), 3.99 mg/L (UCT), 1.12 mg/L and 0.14 mg/L (two MUCT anoxic tanks), and 6.91 mg/L (EPR), respectively.

The anaerobic phosphorus release amount of EPR process was significantly higher than that of other processes, and its anoxic tank has a "one-carbon dual-use" denitrifying phosphorus accumulation reaction, and the denitrifying phosphorus accumulation amount is the highest. Hence, the EPR process was most capable of removing phosphorus.
4. Conclusions
Figure 2 showed that the EPR process had the strongest phosphorus removal ability, while the inverted A\textsuperscript{2}/O process had the strongest nitrogen removal ability. The five processes had basically the same carbon removal ability. The denitrification rate of inverted A\textsuperscript{2}/O process was 91.60%, which was higher than that of other five processes. The denitrifying phosphorus removal occurred in anoxic tank of EPR process with a 6.91 mg/L phosphorus uptake amount. And the anaerobic tank without the disturbed of nitrifying liquid reflux, achieved a phosphorus release up to 24.01 mg/L. The EPR process showed a highest phosphorus removal efficiency. All effluent indicators met the first A level criteria (GB18918-2002) except for the TN removal efficiency, which only met the first B level (GB18918-2002), above that, the process was feasible.

Acknowledgement
This work was supported by the Scientific Innovation Practice Project of Postgraduates at Chang'an University under Grant 300103714014.

References
[1] Ghasemi S M, P Esmaeili and M P Chenar 2020 Enhancement of A2O Process with Integrated Fixed-film Activated Sludge (by GPS-X) 7th International Conference on Chemistry and Chemical Engineering
[2] Suh J I and J H Kim 2019 A Study on the Removal of Nitrogen in A2O Process by Sulfur Denitrification under Low C/N Ratio Condition Journal of Korean Society of Water Science and Technology 27(5) p. 3-11 DOI: 10.17640/KSWST.2019.27.5.3
[3] Wang W, S Y Wang, Q Zhang, L Q Xing, F B Bao and Y Z Peng 2016 Post-anoxic UCT step-feed process in treating municipal wastewater with low C/N ratios China Environmental ence
[4] Abbasi N, M Ahmadi and M Naseri 2021 Quality and cost analysis of a wastewater treatment plant using GPS-X and CapdetWorks simulation programs Journal of Environmental Management 284(1) p. 111993 DOI: 10.1016/j.jenvman.2021.111993
[5] Wang X, S Wang, T Xue, B Li, X Dai and Y Peng 2015 Treating low carbon/nitrogen (C/N) wastewater in simultaneous nitrification-endogenous denitrification and phosphorous removal (SNDPR) systems by strengthening anaerobic intracellular carbon storage Water Res 77 p. 191-200 DOI: 10.1016/j.watres.2015.03.019
[6] Xie S, J Zhao, Q Zhang, J Zhao, S Lei, X Ma and C Yan 2021 Improvement of the performance of simultaneous nitrification denitrification and phosphorus removal (SNDPR) system by nitrite stress Sci Total Environ 788 p. 147825 DOI: 10.1016/j.scitotenv.2021.147825
[7] Zheng X, J Tong, H Li and Y Chen 2009 The investigation of effect of organic carbon sources addition in anaerobic-aerobic (low dissolved oxygen) sequencing batch reactor for nutrients removal from wastewaters Bioresour Technol 100(9) p. 2515-20 DOI: 10.1016/j.biortech.2008.12.003
[8] Administration, C.E.P., Discharge Standard of Pollutants for Municipal Wastewater Plan. 2002, General Administration of Quality Supervision, Inspection and Quarantine of China. p. 13P.; A4
[9] Gang F U, B Dong, Z Y Zhou and T Y Gao 2004 Design Characteristics and Operating Parameters of Inverted AAO Process China Water & Wastewater
[10] Zhang W, X Xue, H Pang, J Zhang and Y Peng 2015 Effect of C/N on performance of AAO-BAF process CIESC Journal DOI: 10.11949/j.ciesc.2015.1157
[11] Lee H, J Han and Z Yun 2009 Biological nitrogen and phosphorus removal in UCT-type MBR process Water Science & Technology A Journal of the International Association on Water Pollution Research 59(11) p. 2093 DOI: 10.2166/wst.2009.242
[12] Wei Z, X Wang, B Li, X Bai and Y Peng 2013 Nitritation and denitrifying phosphorus removal via nitrite pathway from domestic wastewater in a continuous MUCT process Bioresource Technology 143(9) p. 187-195 DOI: 10.1016/j.biortech.2013.06.002