

Article

Comprehensive Analysis of Oxidation Ditch and High-Efficiency Multi-Cycle A²/O Processes Performance in Urban Wastewater Treatment

Jun Liu ^{1,2,3}, Kangping Cui ^{1,*}, Zhen Yan ^{2,3} and Houyun Yang ³

¹ School of Resource and Environmental Engineering, Hefei University of Technology, Hefei 230009, China; liujun_4323@163.com

² Anhui Zhonghuan Environmental Protection Technology Co., Ltd., Hefei 230000, China; yz19880616@163.com

³ Pollution Control and Resource Utilization in Industrial Parks Joint Laboratory of Anhui Province, Hefei 230000, China; youngy@ahjzu.edu.cn

* Correspondence: cuikangping@163.com

Abstract: Oxidation ditch and Anaerobic–Anoxic–Oxic (A²/O) processes have been applied in urban wastewater treatment plants for decades, but the differences between two processes in engineering applications are less studied. Based on the continuous monitoring of Ningyang’s sewage treatment plant (Shandong, China) for one year, this study systematically analyzed the removal efficiencies of nutrients in the oxidation ditch and the modified high-efficiency multi-cycle A²/O processes. The results showed that chemical oxygen demand (COD) and total phosphorus (TP) removal in the modified high-efficiency multi-cycle A²/O process of the Phase II project was better than that in the oxidation ditch process of the Phase I project, and the average concentration of COD and TP in the effluent was 49.9% and 51.7% lower than that in the oxidation ditch process, respectively. The removal rate of ammonia nitrogen (NH₄⁺-N) by the two processes was basically the same, while the total nitrogen (TN) effluent concentration of the oxidation ditch process was 31.4% lower than that in the high-efficiency multi-cycle A²/O process. In summary, the high-efficiency multi-cycle A²/O process had a better treatment performance regarding nutrient removal than the oxidation ditch process under the same conditions. Furthermore, the engineering and operational costs of the high-efficiency multi-cycle A²/O process were lower.

Keywords: oxidation ditch process; high-efficiency multi-cycle A²/O process; urban wastewater; removal rate



Academic Editor: Andreas Angelakis

Received: 8 January 2025

Revised: 27 February 2025

Accepted: 27 February 2025

Published: 28 February 2025

Citation: Liu, J.; Cui, K.; Yan, Z.; Yang, H. Comprehensive Analysis of Oxidation Ditch and High-Efficiency Multi-Cycle A²/O Processes Performance in Urban Wastewater Treatment. *Water* **2025**, *17*, 713. <https://doi.org/10.3390/w17050713>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The acceleration of urbanization has prompted China’s urban sewage discharge volume in 2020 to reach 57.14 billion m³/year [1]. Wastewater treatment plants (WWTPs) have been operating at high load for a long time, seriously affecting the quality of the effluent [2]. Wastewater treatment has become a significant challenge in ecological construction. Improving the efficiency of wastewater treatment plants and reducing the effective concentration of nitrogen, phosphorus, and other pollutants in the effluent are effective ways to solve this problem [3,4]. Currently, oxidation ditches and A²/O processes are widely used in urban WWTPs both domestically and internationally due to their high efficiency of simultaneous nitrogen and phosphorus removal from wastewater, low operating costs, regional selectivity, stable operation, and good shock load resistance [2,5,6]. The oxidation ditches process consists of a groove body, aeration equipment, inlet device, flow diversion,

and mixing equipment. The sewage and activated sludge show a circulating flow that connects the head to the tail in the aeration area, with a long hydraulic residence time and low organic load. While the A²/O process is an anaerobic–hypoxia–aerobic biological process. The organic combination of three different conditions and different types of microbial flora can simultaneously remove organic matter, as well as nitrogen and phosphorus [7].

The wastewater treatment efficiency of oxidation ditches and A²/O processes is significantly dependent on the nitrogen and phosphorus concentration in the wastewater. For example, the removal efficiencies of various nutrients in the effluent from oxidation ditches were consistently above 90% when treating the wastewater with high nitrogen and phosphorus concentrations, which achieved the high requirements of the discharge standard [8]. In contrast, the treatment efficiency of the A²/O process is generally poor, especially the lower efficiency of nitrogen and phosphorus removal [9,10]. In order to solve the above problems of the A²/O process, previous studies constructed an A³/O structure on the basis of the traditional A²/O process by adding a pre-denitrification zone or building the integrated multi-tank anaerobic-anoxic/oxic-A²/O process and implemented a real-time control strategy, which used the “phased isolation tank” technology to change the aeration and water flow path to achieve automatic circulation in eight stages [11,12]. Additionally, some factors, such as the C/N ratio and sludge microorganisms in the wastewater, also affect the treatment efficiency of these two processes to varying degrees [4,6]. Furthermore, the environmental background of WWTPs is also an important factor influencing the treatment efficiency of these two processes besides the characteristics of the wastewater [3,13,14]. It could indicate that the treatment efficiency of these two processes might differ significantly in treating wastewater with different pollutant characteristics. Therefore, selecting an appropriate treatment process for urban wastewater with different pollutant characteristics is crucial to improve treatment efficiency, cost reduction, and achievement of stable and compliant sewage discharge.

In order to clarify the main differences in wastewater treatment and explore a more suitable wastewater treatment process for urban wastewater, characteristics between oxidation ditches and modified high-efficiency multi-cycle A²/O processes should be analyzed. This study selected Ningyang’s sewage treatment plant as a research object, comprehensively analyzed the nutrient removal efficiency, and compared the sludge volume index (SVI) of oxidation ditches and high-efficiency multi-cycle A²/O processes under the condition of consistent influent water quality. The aims of this work are as follows: (1) elucidate the main differences in treatment efficiency of nutrients (COD, NH₄⁺-N, TN, and TP) between the two processes; (2) provide scientific evidence for ensuring the region treatment efficiency and improving the effluent quality; and (3) comprehensively analyze the two processes costs and operating costs.

2. Materials and Methods

2.1. Wastewater Treatment Processes

The Ningyang sewage treatment plant (116°8′26.828″ E and 35°33′27.192″ N) was built in two phases. The wastewater treatment process for Phase I is as follows: coarse screen and pumping station + fine screen and sedimentation tank + anoxic tank + A/O (oxidation ditch) + secondary sedimentation tank + intermediate pumping station + grid flocculation sedimentation tank + fiber bundle filter + disinfection process. The treatment process for Phase II is as follows: coarse screen and pumping station + fine screen and cyclone sedimentation tank + high-efficiency multi-cycle A²/O tank + secondary sedimentation tank + intermediate pumping station + grid flocculation sedimentation tank + V-shaped filter + disinfection process. The effluent achieves Grade A according to the “Pollutant Discharge Standard for Urban Wastewater Treatment Plants (GB18918-2002, China)” [15].

As shown in Figure 1A, the oxidation ditch process of Phase I uses meter exposure, and the aeration equipment is a rotary disk, with a total of 8 units, with a speed of 55–65 rpm. Based on the conventional A²/O process, the tank shape was modified to form a high-efficiency multi-cycle A²/O process (Figure 1B), including the addition of guide walls and pushers in the aerobic section and the division of the aerobic section into multiple groups. The main advantages of this modified A²/O process are as follows: (1) creating a completely mixed mixture + plug flow mode throughout the biological section; (2) using gas flow meters and dissolved oxygen (DO) detectors (which measure the concentration of dissolved oxygen in water) to provide feedback and control the air supply from blowers, forming a gradient dissolved oxygen region in the aerobic section to reduce energy consumption; and (3) increasing the anoxic time and reducing the dissolved oxygen in the aerobic section to achieve efficient denitrification based on the influent water quality with the low C/N ratio (the mass ratio of carbon to nitrogen in wastewater).

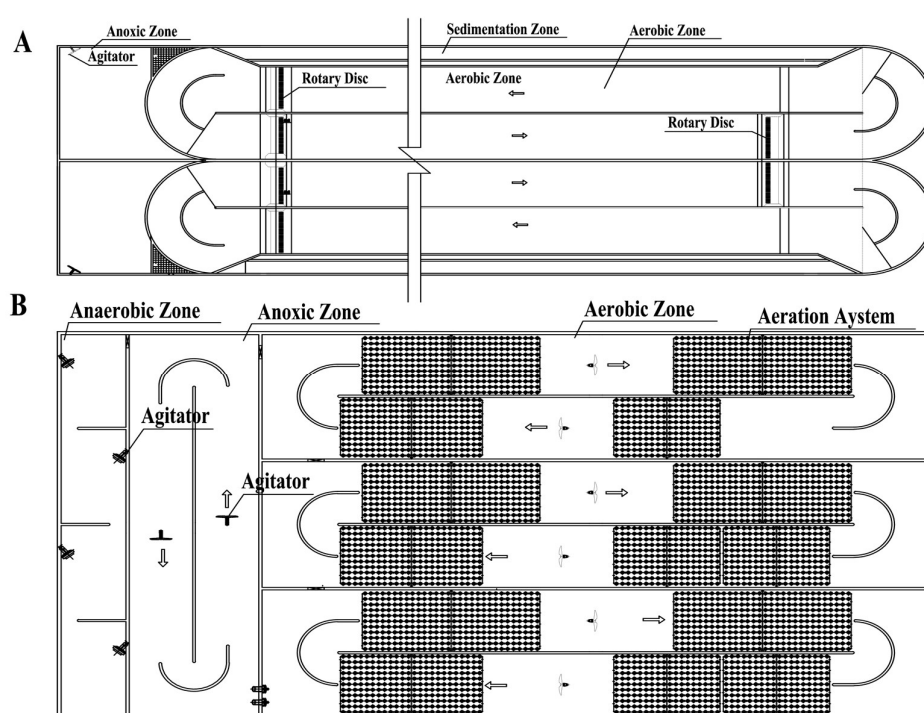


Figure 1. The scheme diagrams for both processes: oxidation ditch (A) and modified A²/O (B) (the arrows: flow direction).

The design and actual influent conditions and water quality characteristics of the wastewater treatment plant are described in Table 1. The designed influent capacity is 40,000 t/d for Phase I and 20,000 t/d for Phase II. The actual average influent values are 33,423.6 t/d and 20,685.1 t/d, respectively. The actual range of influent for Phase I and Phase II is 21,155–45,778 t/d ($p < 0.001$) and 8793–32,281 t/d ($p = 0.0034$), respectively. In terms of water quality, the designed influent values for COD, NH₄⁺-N, TN, and TP are 450, 35, 40, and 4 mg/L, respectively, while the actual average values are 400.8, 22.73, 34.09, and 4.01 mg/L. The actual range of these nutrients is 95.3–964, 14.9–29.0, 17.4–63.2, and 1.02–16.5 mg/L, respectively. Except for TP ($p = 0.95$), all other water quality indicators show significant differences from the designed values ($p < 0.001$).

Table 1. Design and actual influent and effluent characteristics of WWTP.

	Phase I Inflow (t/d)	Phase II Inflow (t/d)	COD (mg/L)	NH ₄ ⁺ -N (mg/L)	TN (mg/L)	TP (mg/L)	Suspended Solids (mg/L)	Temperature (°C)
Design Inflow	40,000	20,000	450	35	40	4	200	-
Design Outflow	-	-	50	5	15	0.5	10	-
Actual Inflow (Mean)	33,423.6	20,685.1	400.8	22.73	34.09	4.01	106	20
Range (95%)	21155–45778	8793–32281	95.3–964	14.9–29.0	17.4–63.2	1.02–16.5	99.6–113.3	15–25
<i>p</i> -value	<0.001	=0.034	<0.001	<0.001	<0.001	=0.95	<0.001	<0.001

As shown in Table 2, the hydraulic retention times (HRTs) for the anaerobic, anoxic, and aerobic zones in Phase I were 3.02, 5.53, and 17.95 h, respectively. While in Phase II, the HRTs were 1.51, 3.02, and 14.92 h, respectively. The sludge return ratio was 100% in both phases. The total nitrogen load was 0.011 kgTN/(kgMLSS·h) in Phase I and 0.005 kgTN/(kgMLSS·h) in Phase II. The surface load of the secondary sedimentation tank was 1.04 m³/(m²·h) in Phase I and 0.62 m³/(m²·h) in Phase II. The nitrified liquid return ratios were 250% and 200% for Phase I and Phase II, respectively.

Table 2. Main operating parameters of two sewage treatment processes.

Parameter	Retention Time (h)			Dissolved Oxygen (mg/L)		Sludge Return Ratio %	Total Nitrogen Load (kgTN/(kgMLSS·h))	Surface Load of Secondary Sedimentation Tank(m ³ /(m ² ·h))	Nitrified Liquid Return Ratio%
	Anaerobic Zone	Anoxic Zone	Aerobic Zone	Anaerobic Zone	Aerobic Zone				
Phase I	3.02	5.53	17.95	0.1–0.2	2.5–3.0	100%	0.011	1.04	250%
Phase II	1.51	3.02	14.92	0.1–0.2	2.0–3.0	100%	0.005	0.62	200%

2.2. Water Quality and Sludge Index Monitoring Methods

The wastewater quality monitoring included five key indicators: COD, TN, NH₄⁺-N, TP, and SVI. The water samples were taken from the sampling sites per day from 1 January 2022 to 30 December 2022, filtered using a 0.22 µm membrane, and stored at 4 °C. The sampling sites were selected at the mixing well of influent and the outlet of the secondary sedimentation tank, and sludge samples were taken from the mixed liquid at the end of the aerobic tank. The COD was measured using the dichromate method (HJ 828-2017) [16], TN was determined through alkaline potassium persulfate digestion with UV spectrophotometry (HJ 636-2012) [17], NH₄⁺-N was analyzed using the Nessler reagent spectrophotometry method (HJ 533-2009) [18], TP was assessed through potassium persulfate digestion and molybdate antimony resistance photometry (GB11893-89) [19], and the SVI was calculated using the sedimentation method (CJ/T221-2023) [20].

2.3. Statistical Analysis

A two-tailed Student's *t*-test was used to quantify the differences in five key wastewater quality indexes during the one-year operation of wastewater treatment processes in Phase I and Phase II, including COD, NH₄⁺-N, TN, TP, and SVI. In addition, in order to quantify the wastewater treatment efficiency of Phase I and Phase II, the removal rates of five key wastewater quality indexes were calculated, respectively. The calculation formula is as follows:

$$\text{Removal rate} = \frac{I_i - O_i}{I_i} \times 100\%$$

where *i* is the sewage quality index, *I_i* is the influent concentration of *i*, *O_i* is the effluent concentration of *i*.

Similarly, a two-tailed Student's *t*-test was used to quantify the differences in the removal rates of five key wastewater quality indexes during the one-year operation of

wastewater treatment processes in Phase I and Phase II. Statistical analysis was performed in SPSS 19.0.

3. Results and Discussion

3.1. The Effect of Two Processes on COD Removal

In urban wastewater, the concentration of COD reflects the pollution status of organic pollutants in the wastewater. After one year of continuous monitoring, the COD concentration of the wastewater in this area was relatively high and had significant annual fluctuations, with the annual average value approaching the design value. The results indicated that the wastewater in this area was characterized by severe organic pollution. The treatment of organic pollutants was key to wastewater treatment in this area. The high variation in the concentration of COD in this WWTP might be related to the influent water quantity, water quality fluctuation (118–997 mg/L), temperature change (high treatment efficiency in summer, low efficiency in winter), sludge concentration control, process operation, and other factors [21]. As shown in Figure 2, compared with the COD concentration and removal rate of the effluent from Phase I and Phase II, it was found that the COD concentration of the effluent from Phase II was 49.9% lower than that of Phase I and the COD removal rate was 27.4% higher than that of Phase I. Although the COD removal rate of the effluent from Phase I was higher than that of previous related studies, its annual average concentration was significantly higher ($p < 0.001$) than the designed effluent concentration, which failed to reach Grade A standard according to the “Pollutant Discharge Standard for Urban Wastewater Treatment Plants (GB 18918-2002, China)” [5,15,22]. Whereas the annual average COD concentration of the effluent from Phase II was far below the designed effluent concentration and had achieved a Grade A discharge standard (Table 3). Therefore, the COD removal effect of the Phase II process was superior to that of the Phase I process. This is related to the use of rotary disk aeration in Phase I, and the use of bottom aeration in Phase II. The bottom aeration efficiency is higher and Phase II adopts a push flow + mixed flow state, which makes the pollutants and microorganisms more sufficient [23].

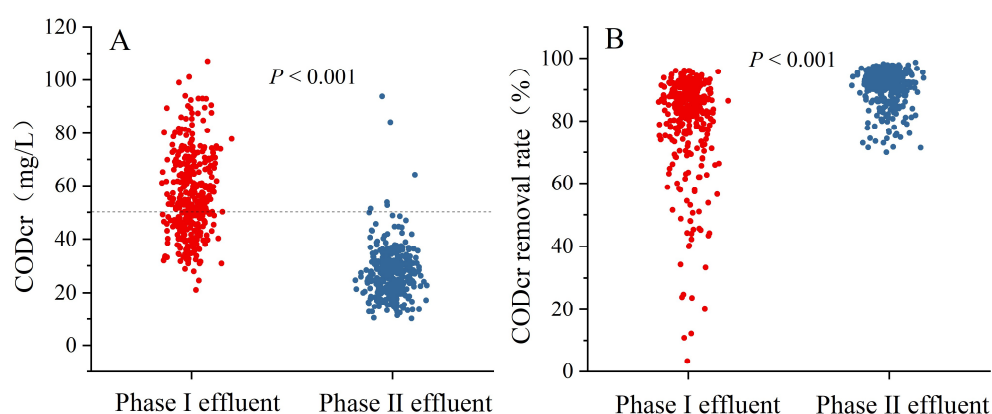


Figure 2. The effluent concentration (A) and removal rate (B) of COD (Phase I: oxidation ditch, Phase II: modified A²/O; dotted line: the COD concentration of design outflow).

Table 3. The effluent nutrients concentration, removal rate, and results of statistical tests.

	Phase I	Phase II	df	t	p
COD (mg/L)	31.6~90.5 (56.7)	13.5~47.0 (27.3)	589.23	31.02	<0.001
COD removal rate (%)	79.8%	90.9%	439.48	12.33	<0.001
NH ₄ ⁺ -N (mg/L)	0.73~6.98 (1.43)	0.59~9.14 (1.45)	713.68	0.15	=0.880
NH ₄ ⁺ -N removal rate	93.50%	93.78%	691.3	0.48	=0.630
TN (mg/L)	3.88~18.3 (9.36)	4.99~24.0 (12.30)	645.48	8.81	<0.001
TN removal rate	71.01%	61.34%	579.42	8.31	<0.001
TP (mg/L)	0.15~1.65 (0.51)	0.02~0.45 (0.17)	418.86	15.035	<0.001
TP removal rate	81.40%	93.24%	501.74	14.09	<0.001
SVI (mg/g)	-	-	225.82	5.1734	<0.001

Notes: Water quality index concentration range (mean value). Average removal rate.

3.2. The Effect of Two Processes on NH₄⁺-N Removal

Nitrogen is an important nutrient in wastewater and a major substance causing eutrophication of water bodies [24]. The annual average concentration of NH₄⁺-N in the wastewater in this area was significantly lower ($p < 0.001$) than the design value. Additionally, compared to other areas, the NH₄⁺-N concentration in this area was lower, indicating that the wastewater in this area does not have a serious NH₄⁺-N pollution problem [7,25,26]. As shown in Figure 3, compared with the NH₄⁺-N concentration and removal rate of the effluent from Phase I and Phase II, it was found that there was no significant difference ($p > 0.05$) between the effluent from Phase I and Phase II, and both basically had reached a Grade A discharge standard. Similarly, previous studies have found that whether it was an oxidation ditch or a highly efficient multi-cycle A²/O process, the removal rate of NH₄⁺-N in wastewater was over 90% [3–6,27]. Therefore, there was no significant difference in the treatment of NH₄⁺-N in wastewater between the two processes (Table 3).

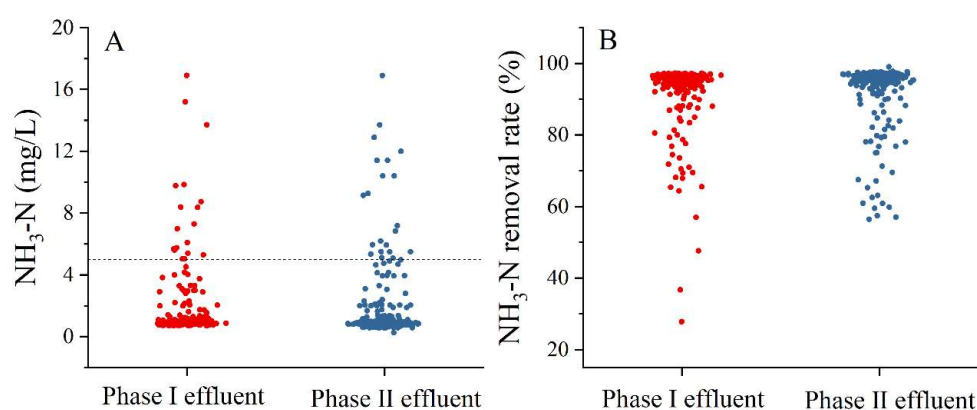


Figure 3. The effluent concentration (A) and removal rate (B) of NH₄⁺-N (Phase I: oxidation ditch, Phase II: modified A²/O; dotted line: the NH₄⁺-N concentration of design outflow).

3.3. The Effect of Two Processes on TN Removal

According to the TN removal efficiency requirements, based on the A²/O process biological nitrogen and phosphorus removal specifications in the “Standard for design of outdoor wastewater engineering” (GB 50014-2021, China) [28], the HRT of the anoxic

zone needs to be 3 h. The HRT of the anoxic zone for Phase II was 3.03 h in actual operation, while the HRT was 5.53 h for Phase I. The TN concentrations of the effluent from both Phase I and Phase II were significantly lower than the design concentration ($p < 0.001$), indicating that the effluent from both phases achieved the discharge standard. As shown in Figure 4, compared with the TN concentrations and removal rates of the effluent from Phase I and Phase II, the TN concentration of the effluent from Phase I mainly ranged from 3.88 to 18.3 mg/L, with an average annual effluent TN concentration of 9.36 mg/L and an average annual removal rate of 71.01%. And the TN concentration of the effluent from Phase II mainly ranged from 4.99 to 24.0 mg/L with an average annual effluent TN concentration of 12.30 mg/L and an average annual removal rate of 61.34% (Table 3). The TN concentration of the effluent from Phase II was higher than that of Phase I by 40.29%, and the removal rate was lower than that of Phase I by 13.09%. The results showed that the TN concentration of the effluent from Phase II was higher than that of Phase I ($p < 0.001$), and the removal rate was lower than that of Phase I. This was related to the longer HRT of the anoxic zone in Phase I, which was approximately 1.83 times that of Phase II. However, compared to other studies, the TN removal rate for both Phase I and Phase II processes was not high [4–6,27]. This might be due to the COD/TN ratio in the wastewater, which could affect the microbial community structure and metabolic activity related to the nitrogen cycle [29–31]. Previous studies have found that the COD/TN ratio of 25 had a better TN removal rate in wastewater, while the average COD/TN ratio in this study was only 11.76 [30]. Additionally, abundant organic matter and microorganisms related to the nitrogen cycle in sludge might also be an important reason for affecting TN removal [32–34].

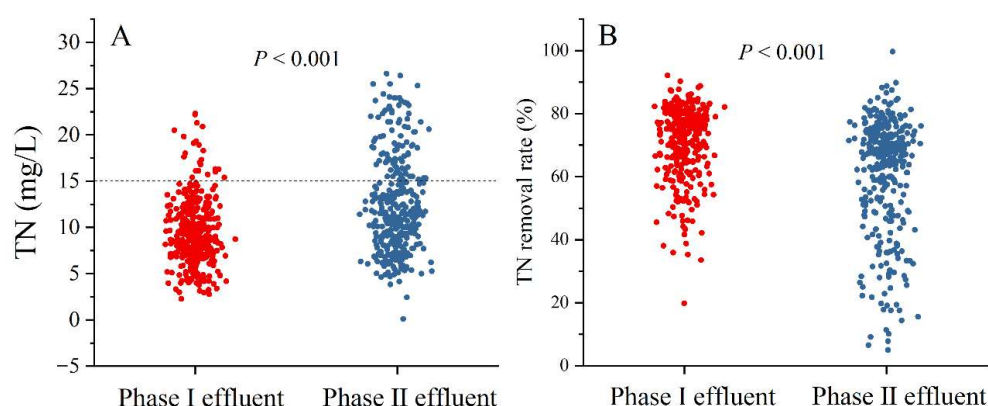


Figure 4. The effluent concentration (A) and removal rate (B) of TN (Phase I: oxidation ditch, Phase II: modified A²/O; dotted line: the TN concentration of design outflow).

3.4. The Effect of Two Processes on TP Removal

Other than nitrogen, phosphorus is an important nutrient in wastewater. Excessive phosphorus discharge can be toxic to aquatic organisms [13]. Therefore, the treatment of phosphorus is more important than that of nitrogen. The annual average concentration of TP in the studied area's wastewater did not show a significant difference from the design value ($p = 0.95$), but it had a large fluctuation (1.02–16.5 mg/L). As shown in Figure 5, compared to the TP concentrations and removal rates of the effluent from Phase I and Phase II, the TP concentration of the effluent from Phase II was significantly lower than that of Phase I ($p < 0.001$), and the removal rate was significantly higher than that of Phase I (Table 3). The TP concentration of the effluent from Phase II was 51.73% lower than that of Phase I, and the TP removal rate was 17.06% higher than that of Phase I. Therefore, the TP removal rate of the Phase II process was better than that of the Phase

I process. Previous studies have also found that the TP removal rate of the oxidation ditch process is not ideal, while the high-efficiency multi-cycle A²/O process has a higher removal efficiency [4,6,35–37]. Additionally, by comparing the average annual effluent TP concentration of Phase I with the design effluent concentration, there was no significant difference ($p = 0.67$), and the effluent from Phase I basically met the requirements of the discharge standard.

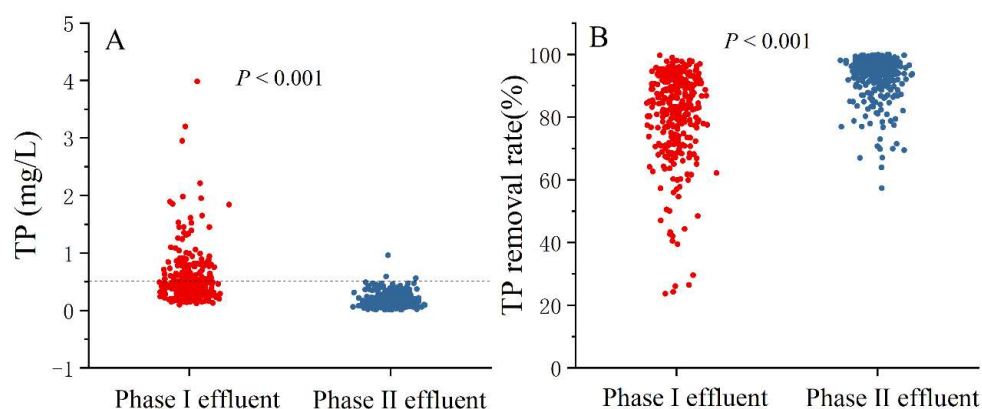


Figure 5. The effluent concentration (A) and removal rate (B) of TP (Phase I: oxidation ditch, Phase II: modified A²/O; dotted line: the TP concentration of design outflow).

3.5. The Effect of Two Processes on Sludge Properties

Sludge contains abundant organic matter and microorganisms related to the nitrogen and phosphorus cycles, which plays an important role in the effectiveness of wastewater treatment [3,4,25,38]. In this WWTP, the mixed liquor suspended solids (MLSS) of Phase I and Phase II were similar ranging from 4000 to 6000 mg/L. As shown in Figure 6, the SVI of Phase I mainly ranged from 54 to 94.8 mL/g with an average annual value of 78.5 ± 11.2 mL/g, and the SVI of Phase II mainly ranged from 60 to 113 mL/g with an average annual value of 87.9 ± 12.4 mL/g. By comparing the sludge properties of Phase I and Phase II, we found that the SVI of Phase II was significantly higher than that of Phase I ($p < 0.01$). The sludge settling performance was an important factor affecting the effectiveness of wastewater treatment [3,26]. In this study, the SVI of the two processes was below 120 mL/g, indicating both processes had good sludge settling performance.

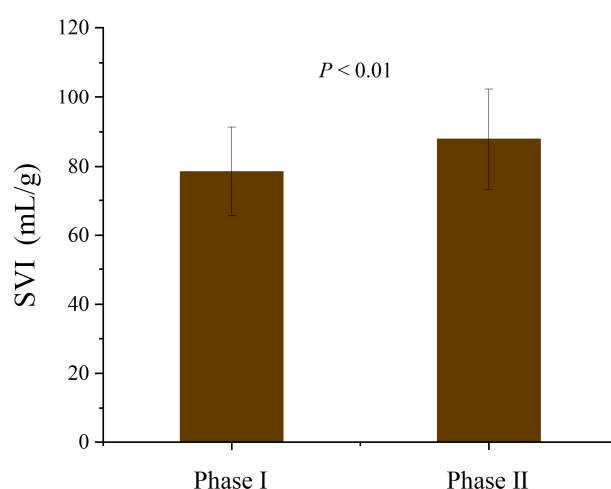


Figure 6. The average sludge SVI of the two processes (Phase I: oxidation ditch, Phase II: modified A²/O).

3.6. Analysis of the Two Processes Costs and Operating Costs

Under the same conditions of influent quality and the achievement of effluent discharge standards in both processes, the total retention time for the oxidation ditch process was 26.5 h, while the total retention time for the high-efficiency multi-cycle A²/O process was 19.45 h. Therefore, the total effective volume of the oxidation ditch process was approximately 1.36 times that of the modified A²/O process. Due to the increase in tank volume, the project cost of the oxidation ditch process also increased, resulting in a higher engineering cost per ton of wastewater.

The design capacity of Phase I of the Ningyang sewage treatment plant was 40,000 t/d, but the actual influent was approximately 33,400 t/d. Meanwhile, the design capacity of Phase II was 20,000 t/d, but the actual influent was approximately 20,700 t/d. The main energy consumption of the biochemical processes in both phases came from the power consumption of the blowers, flow propellers, and internal recycle pumps. Based on the design and equipment power calculation, the electricity consumption was 0.307 kW·h per ton of wastewater. Due to the deviation between the actual influent and the design capacity, the actual electricity consumptions for Phase I and Phase II were approximately 0.363 kW·h and 0.295 kW·h per ton of wastewater, respectively, which were lower than the average electricity consumption of China (about 0.42 kW·h/t). The electricity consumption per ton of wastewater in the high-efficiency multi-cycle A²/O process of Phase II was about 81.27% of that in the oxidation ditch process of Phase I, resulting in lower operational costs of Phase II.

4. Conclusions

This paper systematically studied the performance of the oxidation ditch process and the high-efficiency multi-cycle A²/O process in treating municipal wastewater. Through continuous monitoring over a year, we found that both processes performed well at the Ningyang sewage treatment plant. The COD concentration of the high-efficiency multi-cycle A²/O process in Phase II was 49.9% more than that of the oxidation ditch process in Phase I, and its removal efficiency increased by an average of 27.4% than Phase I. The concentration and removal efficiency of NH₄⁺-N in Phase II were not significantly different from that in Phase I. While the TN concentration of Phase II increased by 40.29% compared with Phase I, and the removal efficiency was 13.09% compared with Phase I. The TP concentration of Phase II was 51.73% higher than that of Phase I, and the removal efficiency increased by 17.06% compared to Phase I. The above data showed that the highly efficient and multi-cycle A²/O process of Phase II was better than the oxidation groove process of the first phase and had lower construction and operating costs. The conclusion of this study provides scientific guidance for wastewater treatment processes in the region and offers a scientific basis for improving wastewater treatment efficiency.

Author Contributions: Conceptualization, J.L. and K.C.; methodology, J.L.; software, J.L.; validation, J.L., Z.Y. and H.Y.; formal analysis, Z.Y.; investigation, J.L.; resources, H.Y.; data curation, J.L.; writing—original draft preparation, Z.Y.; writing—review and editing, K.C.; visualization, Z.Y.; supervision, K.C.; project administration, H.Y.; funding acquisition, K.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ecological Environment Research Project of Anhui Province, grant number 2023hb0010.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: Zhen Yan was employed by Anhui Zhonghuan Environmental Protection Technology Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Jin, Z.; Zhang, X.; Li, J. Impact of wastewater treatment plant effluent on an urban river. *J. Freshw. Ecol.* **2017**, *32*, 697–710. [\[CrossRef\]](#)
- Ren, F.; Sun, Y.; Liu, J. A modified dynamic DEA model to assess the wastewater treatment efficiency: Perspective from Yangtze River and Non-Yangtze River Basin. *Sci. Rep.* **2022**, *12*, 9931. [\[CrossRef\]](#) [\[PubMed\]](#)
- Zeng, W.; Li, L.; Yang, Y. Nitrification and denitrification of domestic wastewater using a continuous anaerobic-anoxic-aerobic (A^2/O) process at ambient temperatures. *Bioresour. Technol.* **2010**, *101*, 8074–8082. [\[CrossRef\]](#) [\[PubMed\]](#)
- Huang, X.; Dong, W.; Wang, H. Sludge alkaline fermentation enhanced anaerobic- multistage anaerobic/oxic (A-MAO) process to treat low C/N municipal wastewater: Nutrients removal and microbial metabolic characteristics. *Bioresour. Technol.* **2020**, *302*, 122583. [\[CrossRef\]](#) [\[PubMed\]](#)
- Huang, X.; Dong, W.; Wang, H. Biological nutrient removal and molecular biological characteristics in an anaerobic-multistage anaerobic/oxic (A-MAO) process to treat municipal wastewater. *Bioresour. Technol.* **2017**, *241*, 969–978. [\[CrossRef\]](#) [\[PubMed\]](#)
- Zhang, S.; Huang, Z.; Lu, S. Nutrients removal and bacterial community structure for low C/N municipal wastewater using a modified anaerobic/anoxic/oxic (mA^2/O) process in North China. *Bioresour. Technol.* **2017**, *243*, 975–985. [\[CrossRef\]](#) [\[PubMed\]](#)
- Ahmed, M.F.; Haider, M.Z.; Majid, H. Modeling of novel processes for eliminating sidestreams impacts on full-scale sewage treatment plant using GPS-X7. *Sci. Rep.* **2022**, *12*, 2986.
- Hadisoebroto, R.; Kamil, I.M.; Notodarmojo, S. Improving Performance of Water Treatment on Oxidation Ditch Using Modification of Reactor Hydrodynamic. *J. Teknol.* **2014**, *69*, 101–104. [\[CrossRef\]](#)
- Li, Y.F.; Yang, J.Y.; Zhang, G.C. Effects of Aeration on Nitrogen and Phosphate Removal with A_2O Process. *Adv. Mat. Res.* **2013**, *622–623*, 1738–1741.
- Ding, X.Q.; Zhao, J.Q.; Chen, Y.; Hu, B.; Ma, B.C. Comparison of nitrogen and phosphorus removal performances for traditional and modified A^2/O process. *Chin. J. Environ. Eng.* **2018**, *12*, 1480–1489.
- Sun, L.; Yue, X.; Zhang, G.; Wang, A. A pilot-scale anoxic-anaerobic-anoxic-oxic combined with moving bed biofilm reactor system for advanced treatment of rural wastewater. *Sci. Total Environ.* **2024**, *933*, 173074. [\[CrossRef\]](#) [\[PubMed\]](#)
- Abualhail, S.; Mohammed, R.N.; Xiwu, L. Integrated real-time control strategy in multi-tank A^2/O process for biological nutrient removal treating real domestic wastewater. *Arab. J. Chem.* **2017**, *10*, S1041–S1054. [\[CrossRef\]](#)
- Zhang, B.; Yu, Q.; Yan, G. Seasonal bacterial community succession in four typical wastewater treatment plants: Correlations between core microbes and process performance. *Sci. Rep.* **2018**, *8*, 4566. [\[CrossRef\]](#) [\[PubMed\]](#)
- Hou, H.; Wang, S.; Peng, Y. Anoxic phosphorus removal in a pilot scale anaerobic-anoxic oxidation ditch process. *Front. Environ. Sci. Eng. China* **2009**, *3*, 106–111. [\[CrossRef\]](#)
- GB18918-2002; Pollutant Discharge Standard for Urban Wastewater Treatment Plants. Ministry of Ecology and Environment of the People's Republic of China: Beijing, China, 2002.
- HJ 828-2017; Water Quality-Determination of the Chemical Oxygen Demand-Dichromate Method. Ministry of Ecology and Environment of the People's Republic of China: Beijing, China, 2017.
- HJ 636-2012; Water Quality-Determination of Total Nitrogen-Alkaline Potassium Persulfate Digestion UV Spectrophotometric Method. Ministry of Ecology and Environment of the People's Republic of China: Beijing, China, 2012.
- HJ 533-2009; Ambient Air and Exhaust Gas-Determination of Ammonia-Nessler's Reagent Spectrophotometry. Ministry of Ecology and Environment of the People's Republic of China: Beijing, China, 2009.
- GB11893-89; Water Quality-Determination of Total Phosphorus-Ammonium Molybdate Spectrophotometric Method. Ministry of Ecology and Environment of the People's Republic of China: Beijing, China, 1989.
- CJ/T221-2023; Standard Examination Methods for Municipal Sludge. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2023.
- Zhu, M.; Yu, X.; Chen, K.; Tan, H.; Yuan, J. Spatiotemporal characteristics and driving factors of chemical oxygen demand emissions in China's wastewater: An analysis based on spatial autocorrelation and geodetector. *Ecol. Indic.* **2024**, *166*, 112308. [\[CrossRef\]](#)
- Zong, Y.; Li, Y.; Hao, K. Influence of transient change of water temperature on pilot-scale anaerobic-anoxic-oxic process under plateau environmental factors. *Appl. Ecol. Environ. Res.* **2019**, *17*, 12191–12202. [\[CrossRef\]](#)
- Haider, M.Z.; Ahmed, M.F.; Waqed, H.H.; Shan-e-hyder, S.; Ali, M. Modeling the effects of sidestreams recycling on wastewater treatment plant performance operated by anaerobic-anoxic-oxic (A^2/O) processes using GPS-X8 simulation. *Results Eng.* **2024**, *22*, 102173.

24. Chen, P.; Wu, J.; Lu, X.; Yu, R. Denitrifying Phosphorus Removal and Microbial Community Characteristics of Two-Sludge DEPHANOX System: Effects of COD/TP Ratio. *Biochem. Eng. J.* **2021**, *172*, 108059. [[CrossRef](#)]
25. Chen, X.; Hu, R.; Xia, M.; Heng, S.; Wang, J.; Liu, Z.; Tian, J.; Lu, X.; Zhen, G. Microalgae Biofilm Barrier to Assist the Simultaneous Nitrogen and Phosphorus Removal in Anammox: Molecular Mechanism on Sludge Granulation and Microbial Metabolism. *Chem. Eng. J.* **2024**, *502*, 157887. [[CrossRef](#)]
26. Ai, N.; Yang, Z.; Lou, B.; Yang, D.; Wang, Q.; Ou, D.; Hu, C. Impact of Stepwisely Reducing Settling Time on the Formation and Performance of Aerobic Granular Sludge. *J. Water Process Eng.* **2024**, *60*, 105117. [[CrossRef](#)]
27. Ma, Y.; Peng, Y.Z.; Wang, X.L. Nutrient removal performance of an anaerobic–anoxic–aerobic process as a function of influent C/P ratio. *J. Chem. Technol. Biotechnol.* **2005**, *80*, 1118–1124. [[CrossRef](#)]
28. GB 50014-2021; Standard for Design of Outdoor Wastewater Engineering. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2021.
29. Jafari, S.J.; Moussavi, G.; Yaghmaeian, K. High-rate biological denitrification in the cyclic rotating-bed biological reactor: Effect of COD/NO₃[−], nitrate concentration and salinity and the phylogenetic analysis of denitrifiers. *Bioresour. Technol.* **2015**, *197*, 482–488. [[CrossRef](#)] [[PubMed](#)]
30. Pan, Z.; Zhou, J.; Lin, Z. Effects of COD/TN ratio on nitrogen removal efficiency, microbial community for high saline wastewater treatment based on heterotrophic nitrification-aerobic denitrification process. *Bioresour. Technol.* **2020**, *301*, 122726. [[CrossRef](#)] [[PubMed](#)]
31. Xiang, Z.; Chen, X.; Bai, J.; Li, B.; Li, H.; Huang, X. Salt-Tolerant Heterotrophic Nitrification and Aerobic Denitrification (HNAD) Bacterium Enhancing a Pilot-Scale Moving Bed Biofilm Reactor (MBBR) Treating Mariculture Wastewater Treatment with Different COD/TN Ratios. *J. Water Process Eng.* **2022**, *50*, 103278. [[CrossRef](#)]
32. González-tineo, P.; Aguilar, A.; Reynoso, A. Organic matter removal in a simultaneous nitrification-denitrification process using fixed-film system. *Sci. Rep.* **2022**, *12*, 1882.
33. Wang, J.; Chon, K.; Ren, X. Effects of beneficial microorganisms on nutrient removal and excess sludge production in an anaerobic-anoxic/oxic (A²/O) process for municipal wastewater treatment. *Bioresour. Technol.* **2019**, *281*, 90–98. [[CrossRef](#)] [[PubMed](#)]
34. Chen, D.; Li, H.; Xue, X.; Zhang, L.; Hou, Y.; Chen, H.; Zhang, Y.; Song, Y.; Zhao, S.; Guo, J. Enhanced Simultaneous Partial Nitrification and Denitrification Performance of Aerobic Granular Sludge via Tapered Aeration in Sequencing Batch Reactor for Treating Low Strength and Low COD/TN Ratio Municipal Wastewater. *Environ. Res.* **2022**, *209*, 112743. [[CrossRef](#)] [[PubMed](#)]
35. Zeng, W.; Li, L.; Yang, Y.Y. Denitrifying phosphorus removal and impact of nitrite accumulation on phosphorus removal in a continuous anaerobic-anoxic-aerobic (A²/O) process treating domestic wastewater. *Enzyme Microb. Technol.* **2011**, *48*, 134–142. [[CrossRef](#)] [[PubMed](#)]
36. You, J.; Tang, S.; Zong, Y.; Shan, H.; Wang, J.; Fu, C. Effects of Adding Different Ratios of Residual Sludge and Food Waste Co-Anaerobic Fermentation Liquid to AAO Wastewater Treatment Process. *J. Water Process Eng.* **2023**, *53*, 103735. [[CrossRef](#)]
37. Zhu, Z.; Zhang, Y.; Hu, L.; Li, Y. Phosphorus Recovery from Municipal Wastewater with Improvement of Denitrifying Phosphorus Uptake Based on a Novel AAO-SBSPR Process. *Chem. Eng. J.* **2021**, *417*, 127907. [[CrossRef](#)]
38. Liu, F.; Zeng, J.; Ding, J.; Wang, C.; He, Z.; Liu, Z.; Shu, L. Microbially-Driven Phosphorus Cycling and Its Coupling Mechanisms with Nitrogen Cycling in Mangrove Sediments. *Sci. Total Environ.* **2025**, *958*, 178118. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.