Pilot study on the treatment of low carbon and nitrogen ratio municipal sewage by A1/O2/A3/A4/O5 sludge-membrane coupling process with multi-point inflow

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Abstract
A new multi-point inflow pre-anoxic/oxic/anaerobic/anoxic/oxic (A1/O2/A3/A4/O5) sludge-membrane coupling process and pilot plant were developed and designed to solve the problem of nitrogen and phosphorus removal of low carbon and nitrogen (C/N) ratio domestic sewage in southern China. The removal effect and transformation rule of organic matter, nitrogen, and phosphorus in the system were studied by changing the distribution ratio of multi-point influent. The average C/N ratio of the influent was 2.09 and the influent distribution ratio was 1:1. When the temperature was 16–25 °C, the average concentrations of chemical oxygen demand (COD), ammonia nitrogen (NH4+-N), total nitrogen (TN), and total phosphorus (TP) in the effluent were 21.31 (±2.65), 0.60 (±0.24), 12.76 (±1.09), and 0.34 (±0.05) mg/L, respectively, and their average removals are 87.3 (±1.2)%, 98.7 (±0.4)%, 74.1 (±1.3)%, and 88.1 (±0.4)% respectively. When the low temperature was 12–15 °C, the average removals were 78.6 (±1.1)% , 90.5 (±1.3)% , 73.7 (±1.13)% , and 86.6 (±1.7)% , respectively. Compared with the traditional anaerobic/anoxic/aerobic (A2O) process under the same conditions, the TN removal was increased by 15.4%, and the TP removal was increased by 22.2%. This system has obvious advantages in treating wastewater with low C/N ratio, thereby solving the problem wherein the effluent of biological phosphorus removal from low C/N ratio domestic sewage was difficult when it was lower than 0.5 mg/L.

Keywords A1/O2/A3/A4/O5 · Sludge-membrane coupling process · Multi-point influent · Low C/N ratio · Urban sewage · Low temperature, A2O · Nutrient removal

Introduction
With the problem of water eutrophication becoming more and more serious, the standard of nitrogen and phosphorus emission is becoming increasingly strict (Zhang et al. 2017a). As a simple simultaneous nitrogen and phosphorus removal process, the traditional anaerobic/anoxic/aerobic (A2O) process is one of the most widely used biological nitrogen and phosphorus removal processes in urban wastewater treatment plants of China because of its simple structure, small control complexity, and difficulty in sludge bulking (Abyar et al. 2018; Yan et al. 2016; Jain et al. 2019). However, the traditional A2O process is a single activated sludge system, and a series of problems can be noted. The competition between denitrifying and phosphorus-accumulating bacteria for carbon source will be caused inevitably because denitrifying and phosphorus-accumulating bacteria live in the same environment (Smolders et al. 2010). At the same time, these bacteria will contradict for sludge retention time (SRT) inevitably (Natalia et al. 2018; Deng et al. 2016; Li et al. 2019). With the continuous improvement of emission standards, the nitrogen and phosphorus removal effect of most urban sewage treatment plants in China was poor due to the lack of carbon source, and the problem of water quality was becoming increasingly prominent. To meet the requirements of...
nitrogen and phosphorus removal, a large number of organic carbon sources need to be added. This approach not only increases the running cost but also causes the waste of carbon source (Rodziewicz et al. 2019; Xu et al. 2018). The contradiction between organic matrix competition and sludge retention time (SRT) is particularly prominent, thereby limiting the further improvement of nitrogen and phosphorus removal efficiency seriously. Thus, the traditional A2O process must be optimized and upgraded.

In recent years, to achieve the standard discharge of low C/N sewage according to the GB18918-2002 1A discharge standard of pollutants for municipal wastewater treatment plants of China, researchers had made improvements on the basis of the traditional A2O process, and many improved A2O processes had been greatly explored and developed (Liu et al. 2020; Peng et al. 2020; Wang et al. 2019b). However, the problem of nitrogen and phosphorus removal in domestic sewage with low C/N ratio had not been solved yet. Autotrophic denitrification (ADB) process could be achieved by autotrophic bacteria using inorganic carbon, which had good denitrification effect on low C/N ratio domestic sewage, as carbon source; however, the generation cycle of autotrophic bacteria was long, and removing phosphorus in sewage effectively was difficult (Wang et al. 2019a; Kiskira et al. 2017). Some researchers added metal ions or reductive substances to the ADB system to achieve phosphorus removal. However, this addition would greatly increase the denitrification cost, which was not favorable in practical engineering applications (Deng et al. 2017; Hu et al. 2019). Multi-point influent A2O process, as an improved A2O process, can use the carbon source in the influent effectively and has significant advantages in the treatment of low C/N ratio domestic sewage. Nan et al. (2018) enhanced the denitrification and phosphorus removal of denitrifying phosphorus-accumulating organisms (DPAOs) in the improved A2O-biological aerated filter (A2O-BAF) double sludge system by step feeding to realize the effective utilization of carbon source in the system. Peng and Ge (2011) successfully enhanced the simultaneous nitrification and denitrification (SNDD) effect of the system by controlling the lower dissolved oxygen (DO) concentration in the aerobic stage and increasing the sludge concentration in the step feeding process, which enhanced the utilization rate of carbon source in the system. In fact, with the change in season, temperature has a great influence on the A2O biological nitrogen and phosphorus removal system (Li et al. 2018), because it affects the activity of functional bacteria in the process, such as ammonia-oxidizing bacteria (AOB), nitrite-oxidizing bacteria (NOB), and phosphorous-accumulating organisms (PAOs) (Liu et al. 2014). At low temperature, the establishment of the community structure of various functional bacteria is difficult, thereby restricting the performance of A2O biological nitrogen and phosphorus removal system (Wei et al. 2010). Thus, the multi-point influent A2O process needs to be further explored, so that it can be applied in practical projects better.

In this paper, a multi-point inflow pre-anoxic/oxic/anaerobic/anoxic/oxic (A1/O2/A3/A4/O5) sludge-biofilm coupling process was designed, and the real domestic sewage was treated: (1) The effects of different multi-point influent ratios on the performance of nitrogen and phosphorus removal of the system were analyzed; (2) the effects of temperature on the performance of nitrogen and phosphorus removal of the system were studied; (3) it was compared with the traditional A2O process. By adjusting the proportion of influent, the utilization rate of carbon source in domestic sewage can be enhanced, and the cost of carbon source consumption in actual operation can be reduced. The SRT contradiction between nitrifying and phosphorus-accumulating bacteria in aerobic tank was alleviated by sludge-membrane coupling. This research provides an effective theoretical basis for the optimization and upgrading of the existing sewage treatment plant and the treatment of domestic sewage with low C/N ratio.

**Materials and method**

**A1/O2/A3/A4/O5 pilot plant**

The schematic plan diagram of the A1/O2/A3/A4/O5 sludge-membrane coupling reactor is shown in Fig. 1a, and the process flow diagram of pilot reactor is shown in Fig. 1b. We designed the reactor according to the previous practical engineering experience and an invention patent of China (CN 107986444 A). The size of the reactor was 1.94 m × 0.45 m × 0.5 m, and the effective volume was 265 L. Furthermore, the device was made of carbon steel anticorrosive material, which was composed of pre-anoxic section (A1), aerobic sludge-biofilm coupling section (O2/O5), anaerobic section (A3), anoxic section (A4), and sedimentation tank (C), with volumes of 21, 75, 38, 56, and 75 L, respectively. The treated sewage enters the A1 and the A3 through the multi-point distribution of inlet water. Part of the sludge in the C returned to the A1, and the excess sludge was discharged. The nitrification liquor in the O5 was returned to the A4. Moving bed biofilm reactor suspended filler with a filling ratio of 30% was added into the O2 and the O5 to enable the nitrifying bacteria to adhere to the filler to solve the contradiction of SRT between nitrifying bacteria and phosphorus-accumulating bacteria. In this project, A1 and O2 were added on the basis of traditional A2O to remove organic carbon sources in raw water by using nitrate in the reflow sludge to reduce the restraining influence of organic matter on the nitrification of O2 reactor. Keeping the total residence time and parameters of section A (A3, A4) and section O unchanged, the traditional A2O comparison device was set up, and the process flow was is in Fig. 10a.
Test water and analytical methods

The real domestic sewage from Ma’anshan Economic Development Zone, Anhui Province, China, was used as the test water. The sewage was a typical urban domestic sewage with low biochemical oxygen demand (BOD₅) and chemical oxygen demand (COD) and high concentration of nitrogen and phosphorus. In general, the C/N ratio between 3 and 5 could meet the requirements of heterotrophic denitrifying bacteria for denitrification well (Hu et al. 2021); however, in this study, the influent C/N ratio was between 1.8 and 2.5, which was a typical low C/N ratio for sewage. The actual influent water quality is shown in Table 1.

The DO and temperature were measured by flexihq30d portable DO meter. The pH was measured by a pH meter. The ammonia nitrogen (NH₄⁺-N), nitrite nitrogen (NO₂⁻-N), nitrate nitrogen (NO₃⁻-N), COD, total phosphorus (TP), total nitrogen (TN), and suspended solid (SS) were determined by Nessler colorimetric method, N-(1-naphthalene)-ethylenediamine spectrophotometric, thymol spectrophotometry, potassium dichromate method, ammonium molybdate spectrophotometry, alkaline potassium persulfate digestion UV spectrophotometry, and gravimetric method, respectively (APHA 2012). The biofilm quantity was determined by shaking washing method to make the biofilm fall off from the filler (Biase et al. 2021) and then by filtration, drying, and weighing methods to obtain the biofilm quantity according to Standard

Table 1. Intake water quality

| Water quality index | pH | COD (mg/L) | BOD₅ (mg/L) | NH₄⁺-N (mg/L) | TN (mg/L) | TP (mg/L) | C/N (BOD₅/TN) |
|---------------------|----|------------|-------------|---------------|-----------|-----------|---------------|
| Range               | 7.0–7.9 | 57.3–199.5 | 100.1–126.9 | 36.5–49.9     | 41.8–54.4 | 1.8–3.8   | 1.8–2.5       |
| Mean concentration  | 7.4 | 160.6      | 102.1       | 45.1          | 48.9      | 2.9        | 2.2           |
Operating conditions

The multi-point influent A1/O2/A3/A4/O5 sludge-biofilm coupling pilot plant was operated from April 1 to December 31, 2019, under the temperature of 12–30 °C. The inoculated sludge was taken from the sludge cake of the South Ma’anshan sewage treatment plant. The mixed liquid volatile SS and mixed liquid SS ratio (MLVSS/MLSS) of the seed sludge was 0.54, the sludge concentration was 36.57 g/L (measured by MLSS), and the inoculation amount of sludge was 2850 mg/L (measured by MLSS). Under the normal operation of the system, the average MLSS in the system was 2032 mg/L. The previous inlet flow research experiment found that the system had the best effect on pollutant removal when the flow was 0.91 m/day. Under the operating condition of keeping the total inlet flow at 0.91 m/day, the system was investigated by adjusting different inlet flow distribution ratios (QA1 segment:QA3 segment). The influences of different temperature ranges on the system were also analyzed and recorded, and the results were compared with the traditional A2O process. Samples were taken daily at 8:30 a.m. and 5 p.m. to measure the different pollutant concentrations of the influent, the end of A1, the end of O2, the end of A3, the end of O5, and the effluent. The operation parameters are presented as follows: the total inflow was 0.91 m/day, the filling ratio of the suspended fillers in the O2 (O2/O5) was 30%, the DO was maintained at approximately 1.5–3.0 mg/L, and the DO of pre-anoxic/anaerobic/anoxic reactors (A1/A3/A4) were controlled in 0.10–0.15 mg/L. The flow of influent and reflux were controlled jointly by valve regulation and manual measurement. The sludge reflux ratio was 75%, and the nitrification reflux ratio was 250%. The total hydraulic retention time (HRT) was 7 h, and the SRT was calculated as 7.5 days by using Formula (1). As shown in Table 2, the multi-point influent operation was divided into five stages (e.g., Run1 to Run5), and the influence of temperature on the process performance was considered. Finally, a comparative study with the traditional A2O device was conducted under the same operating condition. Considering that the traditional A2O nitrogen removal process had been extensively studied, an A2O equipment was added as the comparison group in this study, and too many details about it will not be given. The inflow remained unchanged at 0.91 m³/day, and the removal of pollutants via A2O under the same total HRT was investigated. The volumes in anaerobic/anoxic/aerobic tanks were 38, 77, and 150 L, and the HRT were 1.0, 2.0, and 4 h, respectively:

\[ S = \frac{XV_T}{Q_S X_R} \]  

Results and discussion

Removal performance of COD with different inflow ratios

As shown in Fig. 2, under the fluctuation of COD in influent that ranges from 157.3 to 199.5 mg/L, different multi-point inflow ratios (QA1 segment:QA3 segment) had basically no influence on COD removal. Under the operating conditions of Run1 to Run5, the effluent COD concentrations were 23.93, 21.96, 21.31, 19.97, and 21.80 mg/L, respectively, and the removals were 85.77%, 86.97%, 87.34%, 88.24%, and 87.03%, respectively. Under all operating conditions, the effluent COD was better than the national class A discharge standard of China (GB 18918-2002). As shown in Fig. 3, most of the COD were removed in the A1 and A3, while only a small part of COD was consumed in the A4 and O2/O5. Moreover, with the increase in the influent ratio of A1, the available COD in the A1 was also increasing. Correspondingly, with the continuous decrease in the influent ratio of the A3, the available COD in the A3 and A4 was also decreasing. Under the conditions of Run1–Run5 with different multi-point influent ratios (QA1 segment:QA3 segment), the cumulative total removals of COD in the pre-anoxic/anaerobic/anoxic stage (A1/A3/A4) were 100.96, 115.79, 119.08, 119.87, and 121.41 mg/L, respectively. The cumulative effective utilization ratios of COD in the total COD removal were 70%, 79%, 81%, 80%, and 83%. However, the cumulative removal capacity of the O2/O5 was 43.27, 30.78, 27.93, 29.97, and 24.86 mg/L, respectively. The cumulative removal was 30%, 21%, 19%, 20% and 17%, respectively. Most of the organic matter was consumed in the anaerobic and anoxic stages (Wang et al. 2012). It is considered that the raw water first entered A1 and A3 stages, and most of the COD in influent would be consumed by anaerobic phosphorus release and anoxic denitrification as electron donor, which caused different proportions of multi-point influent to basically have no influence on COD removal (Abyar et al. 2018; Wang et al. 2018).

Removal performance of nitrogen with different inflow ratio

Fig. 4 shows the removal efficiency of NH₄⁺-N with different multi-point influent ratios. Although the influential ammonia nitrogen (NH₄⁺-N) concentration was high and fluctuates
The effluent NH$_4^+$-N concentration was relatively stable, and the effluent NH$_4^+$-N concentration with 97% coverage could reach less than 5 mg/L. The average effluent NH$_4^+$-N concentrations under different operating conditions of Run1–Run5 were 3.94, 0.80, 0.60, 1.47, and 2.95 mg/L, respectively. The removals were 91.31%, 98.28%, 98.69%, 96.71%, and 93.75%, respectively. The system showed strong nitrification capacity. It was considered that most nitrification taken place on the O$_2$/O$_5$ packing biofilm, which prolonged the SRT of nitrifying bacteria and enhanced the nitrification ability of the system (Falahti-Marvast and Karimi-Jashni 2015).

Compared with other operating conditions, the NH$_4^+$-N concentration in the effluent of Run1 decreased first and then increased with the influent distribution ratio. In Run1 operation condition (influent ratio was 3:7), due to the large proportion of influent water in the A4, the NH$_4^+$-N load in the O5 was too large, which exceeded the treatment load of the O5. Nitrifying bacteria could not nitrate NH$_4^+$-N completely in time, thereby increasing the NH$_4^+$-N concentration in the effluent (Wang et al. 2012). Under the conditions of Run2 and Run3 with the influent ratios of 4:6 and 5:5, the effluent NH$_4^+$-N had a better performance, indicating that the operating condition of the system was the best under the inflow distribution mode of Run2 and Run3. However, with the continuous increase in NH$_4^+$-N in Run4 and Run5, the effects of ammonia treatment in Run4 and Run5 were considered better than that in Run1. Although the influent ratio of A1 kept increasing, a large amount of NH$_4^+$-N would be removed through the nitrification of O2 and O5. Moreover, A1, A3, and A4 could produce more alkalinity in the process of denitrification, which was conducive to strengthening the nitrification of O5 tank and improving the removal effect of NH$_4^+$-N in the system. Figs. 4 and 5 show that the

| Run | day | Operating conditions | Water inflow (m$^3$/d) | Temperature (°C) | Influent ratio (Q$_{A1}$/Q$_{A3}$) | Average inflow load (kg/(m$^3$·d)) | COD | NH$_4^+$-N | TN | TP |
|-----|-----|----------------------|-----------------------|------------------|---------------------------------|-----------------------------------|-----|--------|-----|-----|
| 1   | 1–15| 0.91                 | 16–25                 | 3:7              | 0.58                            | 0.15                              | 0.17 | 0.0096 |
| 2   | 16–30| 0.91                 | 16–25                 | 4:6              | 0.54                            | 0.16                              | 0.17 | 0.0100 |
| 3   | 31–45| 0.91                 | 16–25                 | 5:5              | 0.58                            | 0.15                              | 0.16 | 0.0100 |
| 4   | 46–60| 0.91                 | 16–25                 | 6:4              | 0.58                            | 0.15                              | 0.17 | 0.0098 |
| 5   | 61–75| 0.91                 | 16–25                 | 7:3              | 0.57                            | 0.16                              | 0.16 | 0.0099 |
| 6   | 76–106| 0.91               | 26–35                 | 5:5              | 0.58                            | 0.15                              | 0.16 | 0.0100 |
| 7   | 107–137| 0.91            | 16–25                 | 5:5              | 0.57                            | 0.16                              | 0.16 | 0.0099 |
| 8   | 138–168| 0.91            | 12–15                 | 5:5              | 0.58                            | 0.15                              | 0.16 | 0.0100 |
| Traditional | 1–140 | 0.91                | 16–25                 | -                | 0.58                            | 0.15                              | 0.17 | 0.0096 |

Fig. 2 Influence of different inflow ratio on removal efficiency of COD

Fig. 3 Removal of COD along with different inflow ratio
multi-point influent A1/O2/A3/A4/O5 process has a good treatment effect on the removal of NH4+-N in low C/N ratio domestic sewage under the appropriate influent ratio. On the one hand, the addition of A1 and O2 increased the residence time of wastewater in the anaerobic stage, so that DPAOs can fully reserve poly-β-hydroxybutyrate (PHB); on the other hand, the presence of certain nitrate made a large amount of DPAOs in A3, which was conducive to the further improvement of denitrifying nitrogen and phosphorus removal process (Zhang et al. 2018). According to traditional A2O theory of nitrogen and phosphorus removal, a competitive relationship was observed between phosphorus-accumulating and denitrifying bacteria. Reasonable distribution of organic carbon sources in raw water by step feeding was conducive to the realization of nitrogen and phosphorus removal (Nan et al. 2018). In conclusion, the NH4+-N removal was the highest when the influent ratio was 5:5.

Fig. 5 shows the variation law of NH4+-N and NO3--N under various working conditions. It could be seen from Fig. 5 that a large amount of NH4+-N was removed by nitrification in the aerobic section (O2) and the aerobic section (O5), and the NH4+-N in the effluent of the system was very low, which indicated that the aerobic sludge-membrane coupling system had a strong nitrification capacity (Kim et al. 2010). Moreover, with the increasing of the influent ratio of the A1, the NH4+-N in the effluent of O2 was also increasing. Correspondingly, with the continuous decrease in the influent ratio of the A3, the NH4+-N content in the effluent of the aerobic sludge-membrane coupling system was very low. The concentration of NH4+-N in the effluent of O5 was also decreasing. The reason for the increase in NH4+-N in the effluent of aerobic stage (O5) under the condition of Run5 was that the influent ratio of A1 was too high, which led to the high NH4+-N in the effluent of O2, which led to the increase in NH4+-N in the effluent of O5. The research on nitrite nitrogen was omitted in the process of data statistics because its content in the process of system operation was too low. For the variation law of NO3--N in each section of the reactor, it could be seen from Fig. 5 that NO3--N could be effectively removed in A3 and A4. Under the condition of Run1, a large amount of NO3--N was produced in O5 because of the high proportion of influent water in the A3. The NO3--N returned to the anoxic tank (A4) without sufficient carbon source for denitrification (Pan et al. 2019), thereby resulting in a large amount of NO3--N in the effluent. Under Run2 and Run3 conditions, as the inflow ratio of A3 continuously decreases, the NO3--N concentration generated by the nitrification of O5 also declines. The NO3--N generated by O2 and O5 reflux to A4 was denitrified by DPAOs, so the NO3--N content in the effluent was relatively low (Li et al. 2020). Then, under the operating conditions of Run4 and 5, with the further decrease in the influent ratio in A3, the influent carbon sources continued to decrease. When the ratio of COD/TN in the influent was lower than 3, denitrification will be inhibited (Peng et al. 2020). Although the influent ratio of A1 was very high, most of the organic matter was consumed in A1 and O2 sections. Thus, the remaining carbon source could not make up for the carbon source demand of the subsequent units, and the denitrification process was hindered and NO3--N could not be effectively removed, thereby resulting in a high concentration of NO3--N in the effluent, which was consistent with Deng et al. (2016). In conclusion, when the influent ratio was 5:5, the removal effect of NO3--N was the best.

Figure 6 shows the TN removal effect of different multi-point influent ratios. The influent TN concentration was 43.84–57.29 mg/L, and the average influent concentration was 48.91 mg/L. Under the condition of Run1–Run5, the average TN concentrations in the effluent were 17.17, 12.81, 12.76, 14.76, and 17.17 mg/L, and the removals were 66.25%, 74.09%, 74.12%, 70.54%, and 64.86%, respectively. Under the conditions of Run1–Run5, with the continuous increase in the influent ratio in A1, the TN removal first increased and then decreased. Fig. 7 showed the C/N ratio of the influent and its consumption in section A under various working conditions. Fig. 7 illustrates that the average C/N (BOD5/TN) ratios of influent water were 2.11, 2.19, 2.18, 2.17, and 2.20. The C/N ratio (BOD5/TN) consumption in A (A1/A3/A4 cumulative) section under each working condition (Run1–Run5) were 4.42, 5.16, 3.23, 3.10, and 4.17. The C/N ratio in the influent had slight changes, but its consumption in A segment had a great change.

Figure 6 shows that the TN removal effect was the worst under Run1 condition. The high influent ratio of A3 resulted in an excessively high influent NH4+-N load, and the nitrifying bacteria could not transform NH4+-N. In addition, Fig. 7 depicts that compared with Run3 and Run4, the consumption of C/N(BOD5/TN) in A section under Run1 working conditions was higher. However, a large amount of NO3--N in the reflux nitrification solution would lead to insufficient carbon sources.
in A4, so the NO$_3$-N could not be removed in time through the denitrification in the A4 (Fan et al. 2015; Chen et al. 2015). Therefore, the effluent of O5 contained a large amount of NO$_3$-N (Fig. 5). Moreover, a large amount of NO$_3$-N was returned to A1 through sludge reflux. Fig. 3 demonstrates the absence of sufficient carbon source in the A1 to remove a large amount of NO$_3$-N from the return sludge (Moradi et al. 2021), which could also be seen from Run1 in Fig. 5. Under Run2 and Run3 conditions, TN removal efficiency was the best, which was consistent with the NH$_4^+$-N removal effect in Fig. 4. In Run1–Run5, the nitrogen removal effect was mainly affected by the adequacy of the influent carbon source (Fu et al. 2009). Under Run2 condition, the C/N$_{(BOD5/TN)}$ consumption ratio of section A was the highest, which
indicated the sufficient carbon source for denitrification under Run2 condition, so the TN removal was very high, and denitrifying phosphorus removal might exist in the A4. In addition, although the C/N(BOD5/TN) consumption ratio of section A under Run2 condition was much higher than that of Run3, the TN concentration in effluent was similar, indicating that nitrogen removal occurs in the aerobic stage (Yang et al. 2020). This phenomenon could also be seen from the nitrogen change of Run2 in Fig. 5. Under Run2 condition, NH4+-N was significantly reduced in the aerobic sludge-membrane coupling section (O5), whereas the NO3--N content was not significantly increased. The reason for this phenomenon might be SND in the coupling section of O5 and denitrification occurred when NH4+-N was converted into NO3--N (Ye et al. 2020). Under Run3 condition, the C/N(BOD5/TN) consumption ratio of section A was as low as 3.23, which was far lower than the theoretical value of denitrification, but the TN removal was the best. The analysis showed that under Run3 condition, denitrifying phosphorus-accumulating bacteria (DPAOs) exist in A4. In the absence of carbon source, the DPAOs used NO3--N as electron acceptor to achieve NO3--N removal (Li et al. 2020). Therefore, NO3--N in the A4 decreased significantly (Fig. 5). When the influent ratio of A1 was higher than that of A3 (flow ratio was more than 5:5), TN removal began to decline. Fig. 7 illustrates that the C/N consumption ratio of section A was the lowest under Run4 condition, which indicated that denitrifying bacteria lack sufficient carbon source for denitrification, so TN removal was reduced. However, under the condition of Run5, the C/N consumption of section A was relatively high, but the removal effect of TN was poor. The analysis showed that, with the increase in feed water ratio of A1, the carbon source in the influent of A1 could meet the consumption of heterotrophic denitrifiers and phosphorus-accumulating bacteria in A1, and part of carbon source was consumed in O2. However, most of the carbon sources are consumed in the first half of the system, thereby causing the remaining carbon sources to be unable to meet the demand of nitrogen and phosphorus removal in the latter half of the system. Moreover, due to the decrease in the proportion of influent in A3, the available carbon sources in the A3 and the A4 continued to decrease. This phenomenon could be seen from the COD consumption in Fig. 3, which led to the shortage of carbon sources in the latter half of the system. The nitrogen and phosphorus removal was affected. In conclusion, the TN removal was the highest when the influent ratio was 5:5.

Removal performance of TP with different inflow ratios

In the traditional phosphorus removal process, PAOs released phosphorus in the A3, absorbed excessive phosphorus in the aerobic section, and then removed phosphorus through mud drainage (Zhang et al. 2017b). In recent years, with the in-depth study of biological phosphorus removal process, the occurrence of simultaneous nitrogen and phosphorus removal is observed in some cases, and DPAOs gradually come into people’s vision (Lin et al. 2019; Rubio-Rincón et al. 2019; Liu et al. 2016). In this study, the SRT was set as 7.5 days, and the phosphorus removal was achieved by sludge discharge. The contradiction of SRT between nitrifying and phosphorus-accumulating bacteria was solved by adding suspended biological carrier into the system, and the problem of carbon source competition was solved by multi-point influent.

Figure 8 shows that the TP concentration of influent was 1.80–3.82 mg/L, the average influent concentration was 2.90 mg/L, and the influent C/P (BOD5/TP) ratio was 26.31–70.50. Under the operating conditions of Run1–Run5, the TP concentrations in the effluent of the system were 0.44, 0.33,
The TP removal of the system was significantly affected by the proportion distribution of influent, and the removal increased at first and then decreased. The concentration of TP in the effluent was relatively stable, indicating that the process had strong impact resistance.

Figure 8 shows that the effluent concentration of TP was higher and the removal was poor in Run1, Run4, and Run5 (when the influent ratios were 3:7, 6:4, and 7:3). Through calculation, the C/P(BOD5/TP) consumption ratios under each working condition were 38.00, 36.08, 36.54, 39.54, and 39.31, respectively. Under Run1 operation condition, although the C/P consumption ratio was large, the residence time of A3 was correspondingly shorter because of the large influent ratio in A3, and the phosphorus uptake in O5 was insufficient because of the insufficient phosphorus release of the phosphorus-accumulating bacteria in A3 (Li et al. 2016). Moreover, the concentration of NO3--N in the effluent of Run1 was very high, and a large amount of NO3--N (NO3--N = 15 mg/L) entered A1 with the sludge return, resulting in the competition of denitrifying and phosphorus-accumulating bacteria for carbon source (Zeng et al. 2011). Some carbon sources were used for denitrification, which affects the phosphorus release and PHB synthesis of PAOs and the phosphorus absorption in O2. This observation was basically consistent with the results of previous studies (Sun et al. 2020). Under Run2 condition, although the C/P consumption ratio of the system was only 36.08, the phosphorus removal efficiency of the system was the best, with an average removal of 88.77%, and the average phosphorus concentration in the effluent was as low as 0.33 mg/L. The results showed that with the decrease in influent ratio in A3, the residence time of each reaction unit after A3 was extended accordingly, so the phosphorus-accumulating bacteria could fully release phosphorus in A3 and absorb phosphorus in O5. At the same time, with the increase in influent in A1, more phosphorus could be removed by alternating changes of A1 and O2, thereby reducing the pressure on phosphorus treatment in the latter half stage. DPAO was a kind of facultative anaerobic microorganism with denitrification and phosphorus removal under the condition of alternating operation of anaerobic/anoxic environment (Li et al. 2020). The phosphorus-accumulating bacteria could use NO3--N as an electron acceptor to complete the process of excessive phosphorus absorption and denitrification simultaneously through their metabolism, so as to minimize the carbon source demand and realize the double saving of energy and resources (Rubio-Rincón et al. 2019). Denitrifying phosphorus removal could save approximately 50% of COD and 30% of oxygen and reduce about 50% of excess sludge (Liu et al. 2016). Under Run3 condition, the C/P consumption ratio was very low (C/P = 36.54), and the system lacked carbon source, but the phosphorus removal capacity was excellent. As the system operates alternately in anaerobic/anoxic environment, as mentioned above, the possible reason for this phenomenon was the denitrifying phosphorus removal in the system (Zou and Wang 2016), so the system had good removal effect on nitrogen and phosphorus under Run3 condition. The reason the phosphorus removal efficiency of Run3 was slightly lower than that of Run2 might be due to the high content of NO3--N from O2 to A3 under Run3 condition, which led to a large number of carbon sources were consumed in A1 and O2, thereby resulting in the shortage of carbon source in the influent of the second half of the reactor, which affected the anaerobic phosphorus release and aerobic phosphorus absorption of the subsequent process and greatly limited the phosphorus removal effect of the system. At the same time, a large amount of NH4+-N was converted into NO3--N in the aerobic section (O2), thereby resulting in a large amount of NO3--N accumulation. Although higher concentration of NO3--N could promote the enrichment of denitrifying phosphorus-accumulating bacteria, excessive NO3--N would also cause denitrifying and phosphorus-accumulating bacteria to compete for carbon source (Wang et al. 2018). The results showed that the system had a good phosphorus removal effect under Run2 and Run3 conditions, indicating that the influent ratio had a certain impact on the phosphorus removal effect of the system. The appropriate influent ratio could reasonably distribute the
carbon source in the influent to meet the requirements of anaerobic phosphorus release, aerobic phosphorus absorption, and denitrifying phosphorus removal by phosphorus-accumulating bacteria. It had good phosphorus removal effect in the process of domestic sewage treatment with a low C/N ratio.

**Influence of temperature on removal performance of COD, NH$_4^+$-N, TN, and TP**

The influence of temperature on the removal effect of COD, NH$_4^+$-N, TN, and TP is shown in Fig. 9. Temperature had a great influence on COD, NH$_4^+$-N, TN, and TP. When the operating temperature increases from below 15 to 35 °C, the removal of COD, NH$_4^+$-N, TN, and TP in the system also rose continuously. The removal of COD increased from 78.6 to 87.4%; the removal of NH$_4^+$-N increased from 90.5 to 98.7%; the removal of TN increased from 73.7 to 77.6%; and the TP increased from 86.6 to 89.3%. In Fig. 9, the system also had a good removal effect for pollutants under low temperature conditions (12–15 °C). The average concentrations of COD, NH$_4^+$-N, TN, and TP in the effluent were 37.8, 4.2, 12.7, and 0.4 mg/L, respectively, and the effluent quality could meet the effluent standard of national class A discharge standard of China (GB 18918-2002), indicating that the system had a good low-temperature resistance.

**Effect comparison with traditional A2O**

Figure 10 b presents that the concentrations of COD, NH$_4^+$-N, TN, and TP in the influent of traditional A2O were 167.97 (± 1.4), 44.55 (± 0.2), 49.28 (± 1.6), and 2.93 (± 0.5) mg/L, respectively. The concentrations of COD, NH$_4^+$-N, TN, and TP in the effluent were 26.37 (±1.33), 7.59 (±0.56), 12.76 (±1.47), and 0.82 (±0.06) mg/L, respectively, and the removals of COD, NH$_4^+$-N, TN, and TP were 84.3 (±3.7)%, 82.9 (±5.6)%, 64.2 (±2.9)%, and 72.1 (±5.9)%, respectively. In this study, the removal of pollutants by A1/O2/A3/A4/O5 process in the treatment of wastewater with low C/N ratio was improved to different degrees compared with the traditional A2O. Under the same inlet condition, the concentrations of COD, NH$_4^+$-N, TN, and TP in the effluent from A1/O2/A3/A4/O5 process were 121.32 (±1.51), 0.60 (±0.38), 12.76 (±1.15), and 0.34 (±0.04) mg/L, respectively. The removals of COD, NH$_4^+$-N, TN, and TP were increased by 3.6%, 19.1%,
15.4%, and 22.2%, respectively. Compared with traditional A2O, this study has great advantages in pollutant removal. By adding suspended biological carrier into the system, the contradiction between nitrifying and phosphorus-accumulating bacteria in traditional A2O on sludge age (SRT) was solved, and the nitrification capacity of the system was strengthened. The phosphorus removal effect of the system was improved. The problem of carbon source competition between denitrifying and phosphorus-accumulating bacteria was solved by step feeding, and the carbon source allocation was optimized. The denitrifying and phosphorus removal performance of the system was strengthened. Therefore, compared with traditional A2O, the removal of COD, NH$_4^+$-N, TN, and TP and other pollutants had been greatly improved in this study. To sum up, the process could effectively remove pollutants on the basis of effective utilization of carbon source. Even in the treatment of wastewater with low C/N ratio, it also had a good effect of nitrogen and phosphorus removal. It hoped that this process could play a certain reference role in the upgrading and transformation of traditional wastewater treatment plants.

**Conclusion**

The optimum system showed the remarkable performance of pollutant removal. Under the optimum system, the removal of COD, NH$_4^+$-N, TN, and TP could be 87.34%, 98.69%, 74.12%, and 88.12%, respectively. The process overcame the problem wherein the treatment of domestic sewage with low C/N ratio by using the traditional A2O process was difficult when phosphorus is less than 0.5 mg·L$^{-1}$. The system could enable the effluent to meet the discharge standard even without adding additional carbon source. The carbon source in the influent was optimized by multi-point influent. In addition, the system exhibited good low-temperature resistance. Under
low temperature of 12–15 °C, the effluent quality could also meet the discharge standard. Compared with the traditional A2O process, the process had better removal effect on pollutants, and the removal of COD, NH4+-N, TN, and TP could be increased by 3.6%, 19.1%, 15.4%, and 22.2%, respectively. It was of great significance in the treatment of domestic sewage with low C/N ratio, thereby providing a new solution and is a beneficial enlightenment for the treatment of urban low C/N ratio sewage.

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Availability of data and materials The data that support the findings of this study are available from the corresponding author upon reasonable request and I declare that (the/all other) data supporting the findings of this study are available within the article.

Author contribution ZDW modified the paper; ZDW and ZJT wrote the manuscript; ZJ reviewed the rationality of the structure of the paper; ZMK, WML, and ZSH analyzed the data of the paper.

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Declarations

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