International Conference on Hydroinformatics

2014

# Application Of Real-Time Control Strategy To Improve Nitrogen Removal In Wastewater Treatment

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# APPLICATION OF REAL-TIME CONTROL STRATEGY TO IMPROVE NITROGEN REMOVAL IN WASTEWATER TREATMENT

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**Abstract:** Biological nitrogen removal is an important task in the wastewater treatment. However, the actual removal of total nitrogen (TN) in the wastewater treatment plant (WWTP) is often unsatisfactory due to several causes, one of which is the insufficient availability of carbon source. One possible approach to improve the nitrogen removal therefore is addition of external carbon source, while the amount of which is directly related to operation cost of a WWTP. It is obviously necessary to determine the accurate amount of addition of external carbon source according to the demand depending on the influent wastewater quality. This study focused on the real-time control of external carbon source addition based on the on-line monitoring of influent wastewater quality. The relationship between the influent wastewater quality (specifically the concentration of COD and ammonia) and the demand of carbon source was investigated through experiments on a pilot-scale A/O reactor ($1m^3$) at the Nanjing WWTP, China. The minimum doses of carbon source addition at different situations of influent wastewater quality were determined to ensure the effluent wastewater quality meets the discharge standard. The obtained relationship is expected to be applied in the full-scale WWTPs.

**Keywords:** nitrogen removal, carbon source addition, real-time control, on-line monitoring

## 1 INTRODUCTION

In recent years, most wastewater treatment plants (WWTPs) have been upgraded and /or applied advanced control strategies to enhance biological nutrient removal in order to meet increasingly stringent effluent criteria. However, often the removal efficiency for nitrogen is limited by the available COD in the influent. The low carbon availability can lead to the risk of exceeding nitrogen law standard in the effluent, especially when high nitrogen mass loading entered the plant. According to the previous studies, a variety of carbon sources were added into the wastewater treatment system to enhance nitrogen reduction [1-5]. Results demonstrated that this measure was effective [6-10], if organic matter was a limiting factor in the influent with low influent COD. Furthermore, the performance of the WWTPs was not always satisfactory due to the variation of wastewater quality and quantity. Therefore, it is obviously necessary to determine the accurate amount of addition of external carbon source in order to save operation cost and ensure that effluent meets the discharge standard.

The aim of the control strategy of external carbon dosage is to improve nitrogen removal by controlling the external flow rate of the carbon source at lower operational costs. On-line sensors can be applied to the wastewater treatment in the terms of the reliability and stability, which have played an important role in the improvement of the wastewater treatment [11, 12]. Control of external carbon dosage together with internal recirculation flow rate could obtain a certain total inorganic nitrogen concentration in the effluent [13]. Yuan and Keller [14] investigated the integrated control of nitrate recirculation and external carbon addition for a pre-denitrification biological wastewater treatment system. Distinct from ordinary control systems, which typically minimise the variation in the controlled variables, the proposed control system essentially maximises the diurnal variation of the effluent nitrate concentration and through this maximises the use of influent COD for denitrification, thus minimising the requirement for external carbon source. However, this approach seems not easy to be applied to full-scale WWTPs.

As a matter of fact, the biological wastewater treatment system has a denitrification capacity [15-17]. Although external carbon source could improve nitrogen removal treating weak wastewater, it can cause huge cost with the increase of the carbon footprint [18, 19]. However, few literatures apply simple methods to estimate available carbon source in the influent and to consequently determine whether it is sufficient or not. If not, how to determine minimum amount of external carbon source under the premise of effluent quality is still a problem to solve.

This study explored the effectiveness of nitrogen removal from domestic wastewater with addition of an external carbon source in different modes. Feasibility of real-time control of carbon source dosage was investigated depending on the influent wastewater quality using on-line monitoring system in a continuous wastewater treatment process. A pilot-scale plant configured as a pre-denitrification system was operated for 3 months treating domestic wastewater. In order to demonstrate the robustness of the control strategy, daily fluctuant municipal wastewater was fed to the pilot scale reactor. The mechanisms responsible for the achievement of high nitrogen removal are discussed.

## 2 MATERIALS AND METHODS

### 2.1 Experimental plant

The pilot-scale plant was installed in Nanjing WWTP (640,000 $m^3$/d) employing A/O process in Nanjing, China. Figure 1 shows that the reactor has maximum working volume of 1.0 $m^3$. In the process, the influent is continuously introduced into the anoxic tank with 4 chambers via peristaltic pump, and then flows into aerobic tank with 12 chambers. Mechanical mixing and air compressor are separately conducted to provide anoxic and aerobic condition, respectively. Returned sludge and nitrate is taken to the first compartment of the anoxic tank by peristaltic pump.

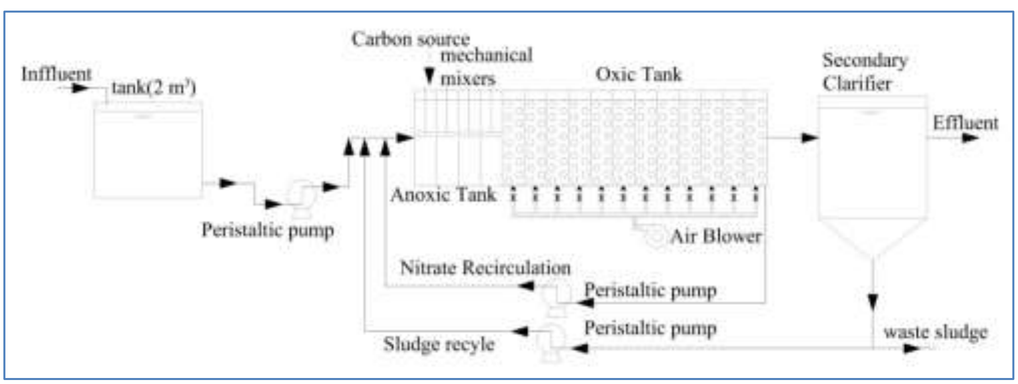


Figure 1. Schematic diagram of the pilot-scale pre-denitrification process

### 2.2 Operation of the system

Raw wastewater was collected from the outlet of aerated grit chamber, a part of a full-scale Nanjing WWTP, China. It was firstly pumped into an intermediate tank (2 $m^3$) before being pumped into the bioreactor. Activated sludge from the aeration tank of the full-scale WWTP mentioned above was taken as an inoculum for the system. The total hydraulic retention time (HRT) of the wastewater in the system (including anoxic and aerobic tank) was controlled at 7 hours. Solids retention time (SRT) of 12～15 days was controlled by excess sludge discharge during the experiments. MLSS in the oxic tank was maintained between 2500mg/L～4000mg/L. All experiments were conducted at temperature (18±1℃). The nitrate recirculation flow rate and sludge recycling flow rate were 1.0 and 0.8 times of the influent flow rate, respectively. The experiments on the effectiveness of nitrogen removal were carried out in three phases: Phase 1 without external carbon source, from Day 1 to Day 40; Phrase 2 with carbon source addition in a fixed mode, from Day 41 to Day70; and Phrase 3 with carbon source addition in a real-time control mode by means of on-line monitoring data, from Day 71 to Day 95. Acetate as carbon supplement was added in the form of a solution of sodium acetate ($CH_3COONa \cdot 3H_2O$). The COD calculated content of sodium acetate is 0.47 mg COD/mgNaAc [6].

### 2.3 Analytical methods

Samples were collected regularly from influent and effluent of the reactor for the off-line measurement of chemical oxygen demand (COD), ammonium ($NH_4^+$-N), nitrate($NO_3^-$-N), nitrite ($NO_2^-$-N),TN, phosphate ($PO_4^-$-P), TP and MLSS according to standard methods [20]. The temperature and DO were determined using YSI 6600 V2 Multi-Parameter Water Quality Sonde (made in USA).

## 3 RESULTS AND DISCUSSION

### 3.1 The characteristics of influent quality

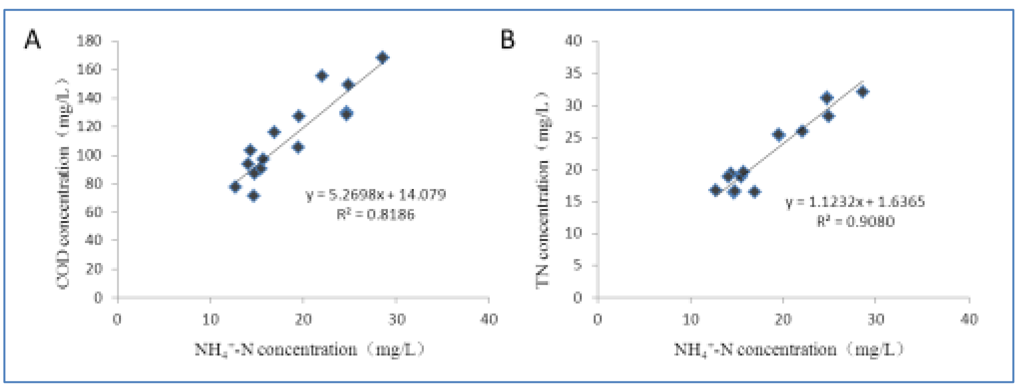


Figure 2. The relationship between influent COD and ammonia(A)；between influent TN and ammonia(B) at the inlet of the reactor

During the Phase 1, the performance of the reactor was good in most cases. However, effluent TN concentration was high under the operation of constant parameters when the ratio of influent COD to TN was small below 5.0. The reason was that available carbon source was limiting for denitrification. As shown in Figure 2(A), it was found that the correlation between influent COD and ammonia concentration in the inlet of the reactor was favorable. Influent COD concentration increased correspondingly with the rise of ammonia concentration. Hence, it was feasible to predict the influent COD value according to the ammonia concentration at the inlet of the system. According to the linear regression, COD could be expressed by Equation (1).

$$Y=5.2698X+14.079 \qquad R^2=0.82 \qquad (1)$$

Where, Y and X represent influent COD and ammonia concentration, respectively.

Figure2(B) showed the relationship between influent TN and ammonia concentration. In the domestic wastewater, nitrogen mainly exists in the form of ammonia, which was a piece of useful information for the nitrogen reduction process with nitrification and denitrification followed. Equation (2) described the relationship between influent TN concentration and ammonia.

$$Y=1.1232X+1.6365 \qquad R^2=0.91 \qquad (2)$$

Where, Y and X represent influent TN and ammonia concentration, respectively.

COD and $NH_4^+$-N are the characterization of the degree of pollution, which could be mainly reduced in the process of wastewater treatment important pollutants. Moreover, Relationship of influent COD and $NH_4^+$-N could provide basis of optimization of process parameters.

### 3.2 The minimum amount of carbon source demand

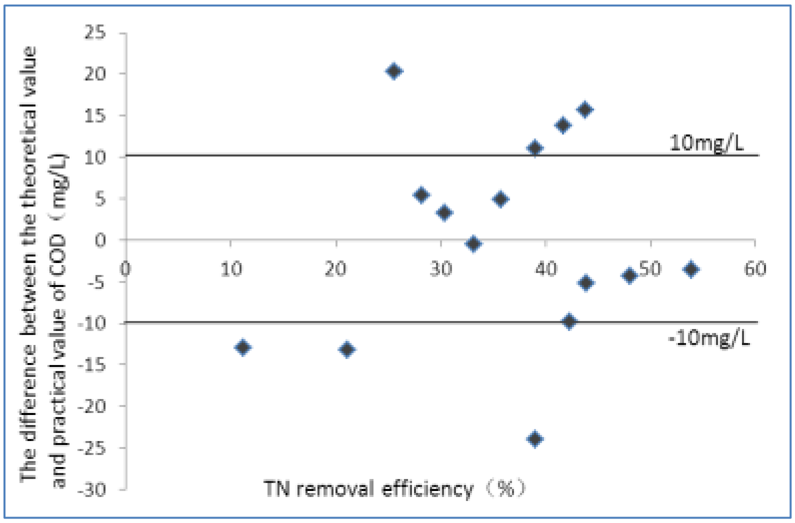


Figure 3. A scatter diagram of TN removal efficiency and the difference between the theoretical and practical value of COD

Determination of the optimal carbon source dosage is a hotspot of the current problems. This study found that the concentration of influent ammonia nitrogen could indicate whether external carbon source was needed or not.

Define a variable $D_0$ to be the difference between the theoretical and practical value of COD (Equation (3)).

$$D_0=D_{COD\text{-}cal}-D_{COD\text{-}obs} \qquad (3)$$

Where, $D_{COD\text{-}cal}$ and $D_{COD\text{-}obs}$ represent theoretical value of COD referred to Equation (1) and observed value of COD, respectively.

As shown in Figure 3, positive values of $D_0$ suggested that carbon source was insufficient as a result of low nitrogen removal efficiency. On the contrary, negative value meant that the carbon source was sufficient. On the other hand, the difference between the theoretical and practical value of influent COD ranged from -10mg/L to 10mg/L, which exhibited approving nitrogen removal performance. Otherwise, the removal efficiency is low or effluent TN concentration was high. Hence, the proper control strategy could be developed based on the above results. There are 3 situations as follows.

（1） $D_0$<-10. It showed that carbon source was adequate, effluent TN could generally meet with discharge standard.

（2） $-10 \le D_0 \le 10$. The carbon source in the influent could be available for nitrogen removal without adding external ones. Results showed that good effluent quality could be obtained when the influent C/N ratio was at a relatively stable range.

（3） $D_0 > 10$. It suggested that carbon source in the influent was insufficient, so external carbon source should be added to the anoxic tank for enhancing nitrogen removal.

Based on the results above, if $D_0 > 10$, accurate amount of sodium acetate as external carbon source can be calculated by Equation (4) as follows:

$$D_1 = (D_0 - 10)/0.47 \quad (4)$$

Where, 0.47 represents the coefficient of sodium acetate converted to COD, 10 represents the upper boundary of the difference between the theoretical and practical value of COD. The accurate amount of carbon source could be calculated according to the results obtained above. Therefore, the optimization of the process treating the wastewater may be achieved by real-time control of carbon source dosage using on-line monitoring data.

**3.3 Performance of the reactor without and with external carbon source by means of on-line monitoring data**

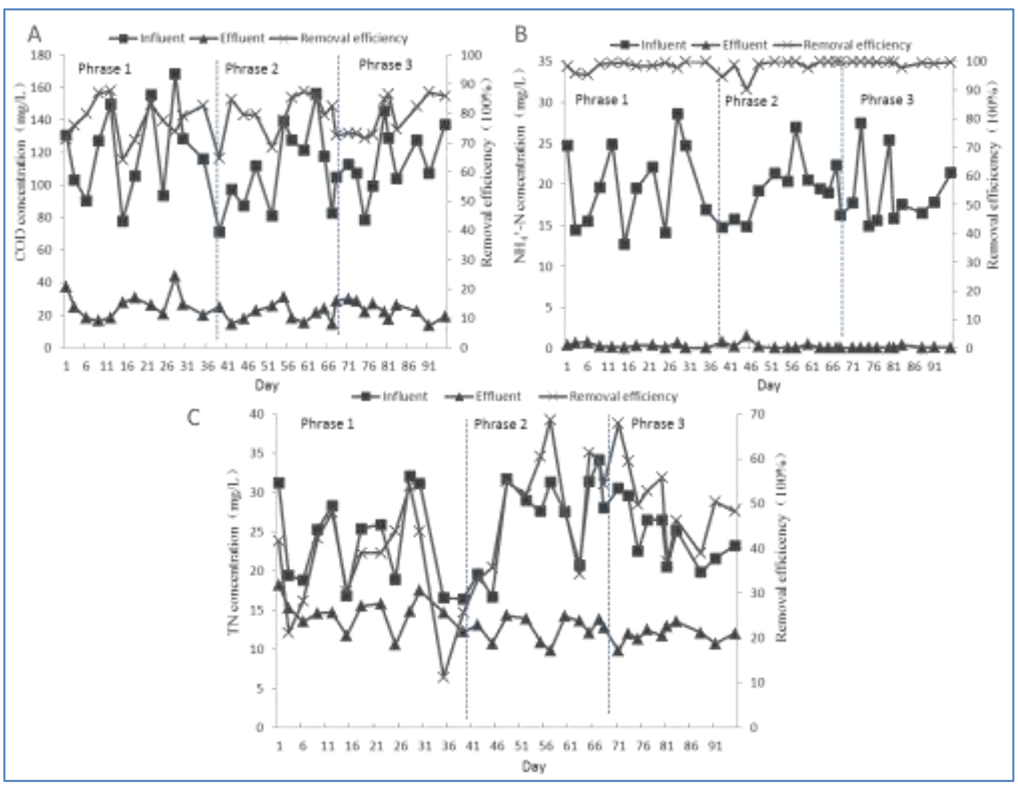


Figure 4. Removal performance of (A) COD, (B) $NH_4^+$-N, and (C)TN during operations.

Figure 4(A) showed that on average about 80% of COD were removed during the study of 3 stages. Ammonia was observed to have almost completely been reduced with more than 90% of removal efficiency described in Figure 4(B), indicating complete nitrification in the reactor, which was uncorrelated with external carbon source addition during operations. The influent COD and ammonia concentration showed a great variability. However, the reactor had good overall performance regardless of the fluctuation of influent quality because low COD and ammonia concentrations in the effluent were found. Nevertheless, there were differences of TN removal ability without and with carbon source addition demonstrated in Figure 4(C). The analysis of the denitrification process was performed. In terms of A/O process, the biological denitrification of such wastewater depends on a number of factors, such as the nitrate recirculation ratio, temperature, pH, availability of organic carbon, and so on. As a matter of fact, when the external carbon source dosage becomes a constant operational condition, a higher nitrogen removal efficiency was obtained during the Phrase 2 compared to Phrase 1. Therefore, available carbon source was a key factor for enhancing nitrogen removal. The process must be, however, performed by the logical necessity to save an expensive carbon source. During Phrase 3, carbon source demand was estimated and calculated by the results mentioned above according to the influent COD and ammonium concentrations by means of on-line monitoring in the inlet of the plant. Then carbon source dosage was adjusted by real-time control. The TN in the effluent was stable and always below 15 mg/L during Phrase 3. However, much sodium acetate was saved during Phrase 3 with real-time control strategy compared to fixed mode for sodium acetate addition.

### 3.4 Mechanisms of high nitrogen removal with minimum carbon source dosage

Conventional biological nitrogen removal process utilizes the activity of nitrifiers and denitrifiers for removing nitrogen from wastewater. A main contributing factor to the improved nitrogen removal in the A/O processes was the occurrence of denitrification in the anoxic tanks. Generally, it should be possible to account for the mass of nitrogen in the influent entering the wastewater treatment system in the following fractions: (1) effluent TKN and nitrate; (2) TKN of the waste sludge in the form of cell synthesis in effluent; (3) nitrogen converted to gaseous nitrogen in the nitrifying activated sludge treatment processes[21]. For the latter two, microorganisms play an important role. Pollutants contained in the wastewater were removed with the aid of microorganisms [22-24]. When the ratio of COD to TN concentration of the influent maintained at a certain extent, denitrifying bacteria and other microbes could form a relatively stable environment. Moreover, while C/N ratio is too large, excessive organic matter in sewage may promote the growth of heterotrophic bacteria, which has the ability of stronger competition for organic matter. It may inhibit the growth of denitrifying bacteria. On the contrary, when available carbon source was seriously insufficient, adding a small amount of substrate as carbon source could prompt the denitrifying bacteria and other bacteria to establish a relatively balanced survival competition environment. Consequently, nitrate in the anoxic tank can be reduced to a certain degree. As long as effluent quality could meet with discharge standard, it was not necessary to minimize nitrate concentration, so there is a limit of the least amount of carbon source dosage. At this point, better performance of nitrogen reduction can be coupled with carbon source quantity control in the lowest level.

Moreover, on the one hand, real-time and accurate control of carbon source dosage could be obtained according to the 24-hour variation in quality and amount of the wastewater by virtue of on-line monitoring sensors, combining with other process operation parameters. So there is further potential for saving carbon source. On the other hand, temperature fluctuations may affect the stability of the system and carbon source dosing quantity. Those aspects should be further evaluated in future research.

## 4 CONCLUSIONS

The study indicated that the system had a flexible capacity for nitrogen elimination, which could be explored for determination of carbon source dosage with the aid of on-line sensors, which are becoming common and affordable. Furthermore, the minimum dosage is found according to the characteristics of influent wastewater quality, which is cost-effective and environmental friendly. Application of real-time control strategy to improve nitrogen removal in full-scale WWTPs with the proposed method is promising.

**ACKNOWLEDGEMENTS**

This work was supported by the “863 Project”-National Plan for High-tech Research and Development (2012AA063302).

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