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Nitrous oxide emissions from a typical northern Chinese municipal wastewater treatment plant

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ABSTRACT

Nitrous oxide (N_2O) emissions from a typical full-scale tertiary municipal wastewater treatment plant (WWTP) in northern China were investigated during spring and summer of 2010. Results showed that the major emission sources of N_2O performed the following descending order: oxic tanks, final clarifier tanks, anoxic tanks, sludge concentration tanks and anaerobic tanks. The total annual N_2O flux from the oxic tanks was the highest and accounted for the majority of total N_2O emissions of this WWTP. The emission factors derived from the field measurements included per capita emissions of 1.73–2.19 g of N_2O person^{-1} y^{-1} and flow based emissions of 2.37×10^{-5}–3.01×10^{-5} g of N_2O (L of wastewater)$^{-1}$. The N_2O emissions accounted for approximately 0.10%–0.13% of the total nitrogen removed in this WWTP. The most significant factors influencing N_2O emissions in this plant were dissolved oxygen concentration and nitrite concentration in the oxic tanks.

Keywords: Wastewater treatment plant; Nitrous oxide; Greenhouse gas emission; Nitrification; Denitrification

1. Introduction

As an important greenhouse gas (GHG) accounting for around 6% of the heating effect of GHGs in the atmosphere, nitrous oxide (N_2O) has a long atmospheric lifetime (approximately 120 years) and heat trapping effects — about 300 times more powerful than carbon dioxide [1]. Global average atmospheric concentration of N_2O has increased from about 270 parts per billion by volume (ppbV) in 1750 to 319 ppbV in 2005. In the last two decades, atmospheric concentration of N_2O continued to increase at a rate of 0.25% per year. Nitrous oxide is produced by both natural and human-related sources. Primary human-related sources of N_2O are agricultural soil management, animal manure management, wastewater treatment, mobile and stationary combustion of fossil fuel, and nitric acid production [2]. N_2O emissions from wastewater treatment were estimated to contribute 26% to the total GHG emissions (CO_2, CH_4 and N_2O) of the water chain, which consists of drinking water production, water transport, wastewater and sludge treatment and discharge [3].

The biological nutrient removal (BNR) processes employed extensively in modern municipal wastewater treatment plants (WWTPs) have been found to be an important emission source of anthropogenic N_2O [2].

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With the increasingly stringent effluent standards implemented in China, nitrogen removal becomes a major task in municipal WWTP's operation. At present, the anaerobic/anoxic/oxic (A/A/O) process is one of the most popular BNR processes in China's large-scale municipal WWTPs for its high nitrogen removal efficiency. The A/A/O process consists of nitrification and denitrification steps, where significant amounts of N_2O could generate and emit under certain conditions [3].

Many studies on the nitrous oxide emissions from WWTPs in some developed American and European countries have been reported [4–7], but so far there are no literature reports of N_2O emissions from China's WWTPs. Czepiel et al. [4] first studied one small BOD removal WWTP in Durham, USA and calculated the per capita and flow based emissions factors which were adopted by IPCC for the calculation of N_2O emissions from WWTPs [1]. However, the WWTP involved in this report is much smaller both in treatment capacity (4000 $m^3\ d^{-1}$) and serving population (12,500) than the typical full-scale WWTP in China, which has a capacity greater than $1\times10^5\ m^3\ d^{-1}$ and serves a population more than 5×10^5. Besides, the traditional aerobic process employed in Durham plant was relatively simple and its nitrogen removal efficiency was relatively low. So the emission factors derived from this plant might not accurately reflect the nitrous oxide release from WWTPs in China. China is one of the largest GHG emitters with the largest population in the world, but China's GHG emission data collection work lagged far behind the developed countries and large amounts of emission data used presently were referred to foreign reports. Therefore it is very important to collect N_2O emission data and calculate the emission factors for better quantification of the GHG emissions and further technical assessments of mitigation options in China's WWTPs. In this study, N_2O emissions from a typical full-scale A/A/O municipal WWTP in northern China were measured, and the major emission sources were identified. Factors influencing the N_2O fluxes were also investigated.

2. Methods

2.1. Field site

The field sampling experiment was carried out at a full-scale tertiary municipal WWTP in Jinan, a metropolis in northern China. The WWTP has a treatment capacity of $3\times10^5\ m^3\ d^{-1}$ and a serving population of about 1,500,000. The detailed process configuration is shown in Table 1. The wastewater treated in this plant is mostly domestic sewage with an average influent COD of 200 mg L^{-1}, an average suspended solids concentration (SS) of 150 mg L^{-1} and total nitrogen (T-N) of 25 mg L^{-1}. The effluent from this WWTP can meet the most stringent effluent standards in China: COD < 50 mg L^{-1}, SS < 10 mg L^{-1}, and total nitrogen < 10 mg L^{-1}. The plant's nitrogen removal efficiency is high and larger amounts of N_2O might be produced as an intermediate product during the biological nitrogen removal process under certain conditions.

Table 1
The wastewater treatment process configuration of the Jinan WWTP

Processing unit	Water surface area (m^2)	Volume (m^3)
Influent pump station	45	450
Aerated grit chambers	350	1225
Anaerobic tanks	6400	16000
Anoxic tanks	6300	44600
Oxic tanks	9400	65800
Final clarifier tanks	12800	38400
High density settler tanks	1020	5200
High efficiency fiber filter beds	840	8200
Sludge concentration tanks	2900	8700

A/A/O process is used in this plant for high nitrogen and phosphorus removal efficiency, achieved by a combination of anaerobic tanks, anoxic tanks and oxic tanks. The A/A/O process can be divided into three stages. Firstly, the wastewater and the external returned activated sludge flow into the anaerobic tanks, with the agitator set to prevent sedimentation of material suspended in the wastewater. Secondly, the wastewater flows into the anoxic tanks with propellers to control water flow, where denitrification and nitrogen removal occur. Finally, the wastewater enters the oxic tanks with aeration equipment, where nitrification and phosphorus removal occur and BOD_5 in the wastewater undergoes further decomposition by aerobic bacteria present in the tanks. In order to enhance the phosphorus and SS removal efficiency, a set of high density settler tanks and high efficiency fiber filter beds are employed respectively following the final clarifier tanks. The treated water moves to the UV disinfection unit and is subsequently released into the receiving river. The simplified wastewater treatment process is depicted in Fig. 1 and the detailed sludge flow is omitted in the figure. The sludge treatment process is relatively simple: the waste activated sludge discharged from final clarifier tanks first enters sludge concentration tanks for thickening, and then is transferred to sludge centrifugal dewatering machines. The dewatered sludge is transferred by screw conveyor to an open yard for drying and subsequently transported outward for landfill or other disposal.

2.2. Sampling and analysis

Nitrous oxide flux was measured from each processing unit of the Jinan WWTP, i.e. influent pump station, aerated grit chambers, anaerobic tanks, anoxic tanks,

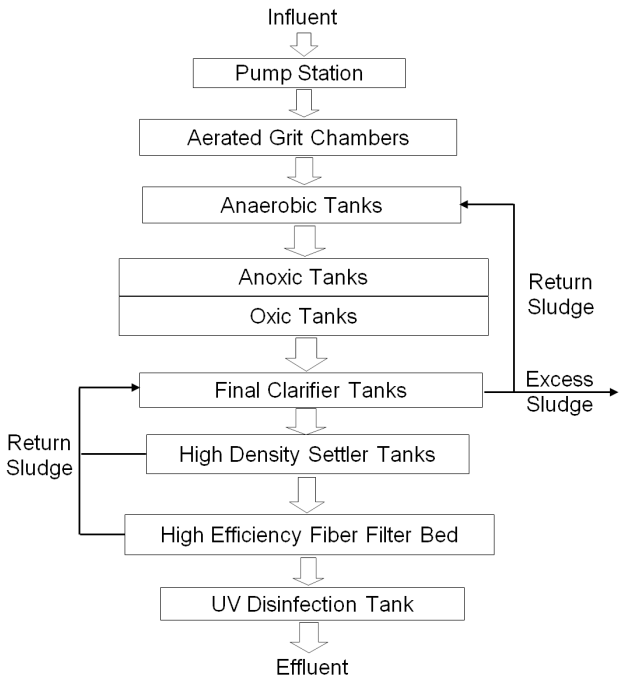

Fig. 1. Simplified wastewater treatment process diagram of the Jinan WWTP.

oxic tanks, final clarifier tanks, high density settler tanks, high efficiency fiber filter beds and sludge concentration tanks. The sampling was conducted jointly by two groups of students on Monday, Wednesday and Friday of each week from March to June, at approximately the same time of each sampling day. The specific field sampling time was from 8 a.m. to 5 p.m., and the sampling order was in accordance with the direction of wastewater flow. The spatial variability of measured N_2O fluxes from each processing unit was examined previously. Results showed that the N_2O flux changed gradually with the dissolved oxygen concentration along the wastewater flow in each wastewater processing unit. In the wastewater processing units with large spatial variability, gas samples were collected from multiple points to obtain the mean value of N_2O fluxes. The sampling point positions were determined by the dissolved oxygen change and the water surface area. The water surface can be divided into two categories: aerated liquid surfaces (in aerated grit chambers and oxic tanks) and nonaerated liquid surfaces (in the remaining processing units).

2.2.1. Wastewater surface gas sampling

An emission isolation flux hood technique was used to measure fluxes from nonaerated wastewater surfaces. The diameter of the flux hood was 0.41 m and sampling area was 0.13 m^2. The flux hood with a thermistor mounted inside was floated and manually held in place during gas sampling to minimize hood movement caused by water surface turbulence. Gas samples were collected in 60-mL polypropylene syringes at 2-min intervals for 10 min. The gas flux was calculated by the equation from Czepiel's article [4]. On the other hand, a bag technique was used to measure N_2O fluxes from aerated liquid surfaces. A 40 L polyethylene sample bag was fastened to the inside of a plastic support frame. When collecting sample, the bag was emptied and the support frame was immersed several inches into the liquid. The dissolved gas was stripped from the liquid during aeration and filled the collection bag. Then the samples were withdrawn from the bag in 60-mL polypropylene syringes. The gas flux was also calculated by the equation from Czepiel's study [4].

2.2.2. Dissolved gas sampling

To collect samples of gas dissolved in wastewater of the processing unit, the headspace gas method was used as described by Kimochi, et al [6]. 30 mL each of water and argon gas were sealed into a 50-mL syringe, and 1 mL of 2 mol L^{-1} H_2SO_4 was then added to reduce microbial activity. After vigorous shaking, the syringe was left at room temperature for 1 h without moving it. The resulting gas phase in the syringe was collected as a gas sample. Then the dissolved N_2O concentration was calculated based on Henry's Law using equilibrated headspace N_2O concentration.

2.2.3. Analytical methods of water and gas samples

To determine dominant factors affecting N_2O production and emission, water samples were collected at the sampling site. Dissolved oxygen concentration (DO), pH and water temperature were measured in situ. COD, T-N, NH_4^+-N, NO_3^--N and NO_2^--N were measured in lab in accordance with the standard methods for examination of water and wastewater [8]. Analysis for N_2O concentration of the gas samples were carried out using a gas chromatograph equipped with an electron capture detector (ECD) and stainless steel packed columns of Porapak Q as described by Keller et al. [9].

2.2.4. Statistical analysis

Nitrous oxide emissions data were examined for statistical distribution to determine the appropriate form of statistical analysis. N_2O flux data from the oxic tanks were found to be log-normally distributed, requiring the application of parametric statistics to the data in log-transformed form. All other sample data were determined to have been drawn from normally distributed populations, permitting application of parametric statistics. Relationships between N_2O emissions and water quality parameters were examined using linear regression techniques.

3. Results and discussion

3.1. N_2O fluxes from unit operation

N_2O can be produced during nitrification and denitrification processes in wastewater treatment plants [5–7]. With relative high water solubility [10], N_2O emission from wastewater is not very fast. The field sampling and measurement indicated that N_2O emission occurred in every processing unit. During the experimental period a similar flux variation trend was obtained among different processing units at different sampling days, measurement data on May 14th, which is shown in Fig. 2, was used to facilitate the following analysis.

3.1.1. Oxic tanks

The maximum of N_2O flux occurred in the oxic tanks, which was 720 mg m^{-2} d^{-1}. This result can be explained by the mechanism of N_2O production. Large quantity of nitrous oxide could be generated as an intermediate product during the nitrification process in the oxic tanks and emit from the liquid phase due to the intensive mechanical aeration stripping in this wastewater processing unit.

3.1.2. Aerated grit chambers and influent pump station

The N_2O fluxes from the aerated grit chambers and influent pump station were the second (559 mg m^{-2} d^{-1}) and the third highest (268 mg m^{-2} d^{-1}), respectively. The high nitrous oxide fluxes from these two unit operations were caused by the N_2O formation during the anaerobic or aerobic biological nutrient decomposition processes naturally occurring in the sewer systems. The generated nitrous oxide could subsequently be released from liquid phase in influent pump station by water turbulence and in aerated grit chambers by intensive mechanical aeration.

3.1.3. Other unit operations

Nitrous oxide could be generated in the anaerobic tanks and anoxic tanks during the denitrification process occurring in these two units due to limited dissolved oxygen concentration. For the N_2O accumulation along the wastewater flow, the nitrous oxide flux from anoxic tanks (64 mg m^{-2} d^{-1}) was higher than that from anaerobic tanks (40 mg m^{-2} d^{-1}).

Though the high density settler tanks and high efficiency fiber filter beds were set behind the final clarifier tanks, the fluxes from these two units were higher than that from the clarifier, the water turbulence and agitation in the high density settler tanks and the fiber filter beds could explain the results. The N_2O flux of (94 mg m^{-2} d^{-1}) from the sludge concentration tanks came from both the dissolved nitrous oxide in the waste activated sludge and regenerated nitrous oxide under anaerobic conditions in this unit.

From the above analysis, it could be found that the N_2O fluxes from some processing units were relatively low and accounted for less than 10% of that from oxic tanks and aerated grit chambers, but they could not be neglected because the total annual fluxes calculation of the Jinan WWTP needed to multiply the large water surface area of these processing units, as shown in Table 1.

3.2. Dissolved N_2O concentration

Dissolved N_2O concentration in each wastewater treatment unit was measured at roughly 1-week interval at the same sampling point as the gas flux measurement during the experimental period. The dissolved gas analyses from different sampling days showed a similar flux variation trend among the wastewater processing units, which was different from the N_2O emission fluxes variation trend as shown above. A typical dissolved nitrous oxide concentration comparison measured on May 14th is presented in Fig. 3. The concentration of dissolved N_2O in the influent pump station and aerated grit chambers were still much higher than that in other wastewater treatment units, which was consistent with and thus led to the higher N_2O fluxes from these two units. Although the N_2O flux from oxic tanks was the highest, the dissolved N_2O concentration in this unit was not very high due to the sufficient aeration in this unit which stripped

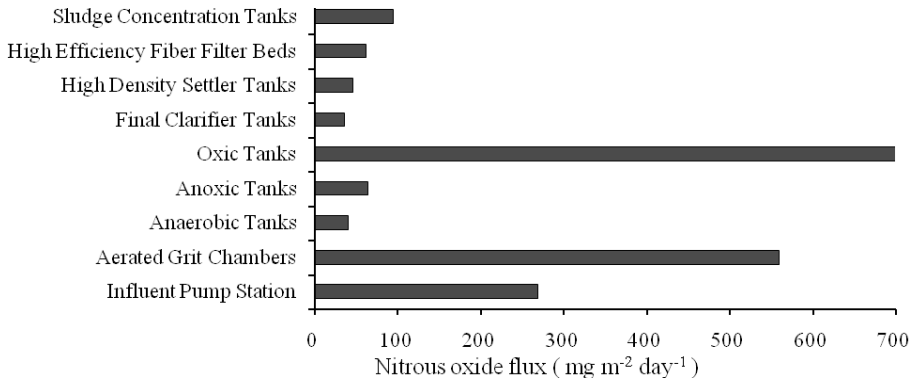

Fig. 2. N_2O fluxes from each processing unit of the Jinan WWTP.

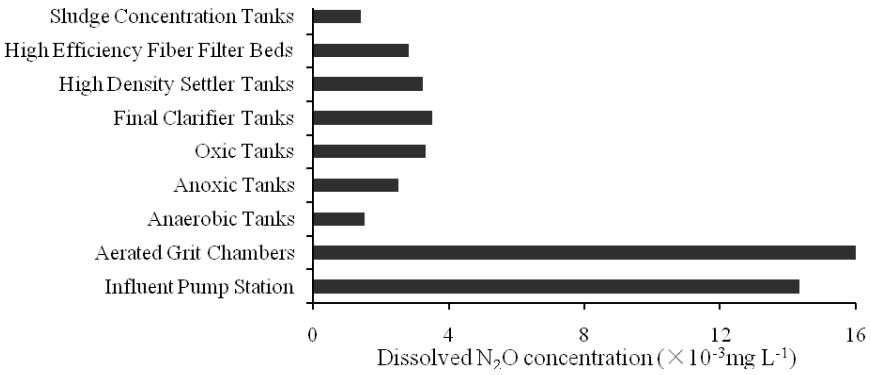

Fig. 3. Dissolved N_2O concentration of wastewater in each processing unit.

most of the N_2O dissolved in wastewater. The dissolved N_2O concentration in anoxic tanks was higher than that in anaerobic tanks, which was caused by N_2O accumulation during denitrification process and was consistent with the N_2O flux variation between these two units. As analyzed in 3.1.3, the water turbulence and agitation in the high density settler tanks and high efficiency fiber filter beds resulted in higher N_2O fluxes from these two units than that from final clarifier tanks; they also led to a lower dissolved N_2O concentration in these two units than that in clarifier tanks. The dissolved N_2O in effluent water from this WWTP could result in subsequent N_2O emissions from the receiving rivers, which could be another important N_2O emission source that needed for further investigation.

Table 2
Total annual N_2O fluxes from the Jinan WWTP

Processing unit	N_2O flux ($\times 10^3$ g y^{-1})
Influent pump station	3.23–5.37
Aerated grit chambers	58.31–75.86
Anaerobic tanks	80.24–101.32
Anoxic tanks	123.61–152.84
Oxic tanks	2026.34–2743.76
Final clarifier tanks	145.57–189.23
High density settler tanks	11.35–20.57
High efficiency fiber filter beds	12.27–23.49
Sludge concentration tanks	93.37–113.25
Total	2602.25–3293.82

3.3. Total annual N_2O fluxes

The calculation of the total annual N_2O fluxes (g y^{-1}) from the processing units considering the entire water surface areas is more valuable for better quantifying the N_2O emissions from this WWTP. During the experimental period (from March to June), the air temperature increased from 0°C to 37°C, and the wastewater temperature rose accordingly from 12°C to 24°C, covering the temperature rang of a whole year in Jinan. Therefore the N_2O fluxes obtained from the experiment could reflect the N_2O emission variations throughout a year. The total annual N_2O flux range could be figured out from the minimum and maximum daily N_2O emissions.

The total annual N_2O flux range from each processing unit is shown in Table 2. The dominant N_2O emission sources were found to be in the following descending order: oxic tanks, final clarifier tanks, anoxic tanks, sludge concentration tanks and anaerobic tanks. The total annual fluxes showed different variation trends from the flux per unit area per day (mg m^{-2} d^{-1}) because there was large difference in water surface area between different processing units. The total annual N_2O fluxes from the influent pump station and aerated grit chambers were low due to their small water surface areas, although their N_2O fluxes per unit area per day (mg m^{-2} d^{-1}) were very high. The total annual fluxes from the final clarifier tanks, anoxic tanks, sludge concentration tanks and anaerobic tanks were high for their large water surface areas. The annual nitrous oxide fluxes from the oxic tanks were the highest and accounted for the majority of total annual N_2O emissions of the whole WWTP, because the oxic tanks had the second largest water surface area and the maximum flux per unit area per day (mg m^{-2} d^{-1}).

3.4. N_2O emission factors

The total annual N_2O fluxes from this WWTP ranged from a minimum of 2.60×10^6 g y^{-1} to a maximum of 3.29×10^6 g y^{-1} based on the flux data from each wastewater processing unit. Considering the population served by this plant (about 1,500,000) and the treatment capacity (3×10^5 m^3 d^{-1}), the emission factors were per capita emissions of 1.73–2.19 g of N_2O $person^{-1}$ y^{-1} and flow based emissions of 2.37×10^{-5}–3.01×10^{-5} g of N_2O (L of wastewater)$^{-1}$. After calculation, the N_2O emissions accounted for

approximately 0.10%–0.13% of the total nitrogen removed in the Jinan WWTP. Compared with the emission factors from Czepiel et al. [4], the per capita emissions of Jinan WWTP was similar to that from Durham plant (3.2 g of N_2O person^{-1} y^{-1}), but the flow based emissions was significantly larger than that from Durham plant (1.6×10^{-6} g of N_2O (L of wastewater)$^{-1}$). The total nitrogen removal efficiency in Jinan WWTP was much higher than that in Durham plant. Therefore large quantity of N_2O might be generated and emitted from wastewater as an intermediate product during the biological nitrogen removal process, which could result in the obviously high flow based emissions in Jinan WWTP. If these measurements are typical for nitrous oxide emissions from municipal WWTPs in China, after scaled on a national basis, an estimated N_2O source strength of 0.95–1.20 Gg y^{-1} (1 Gg =10^9 g) for all China's municipal WWTPs could be obtained based on the total treated domestic sewage flow of China.

3.5. Factors influencing N_2O emissions

Studies on lab-scale systems showed that a number of factors could influence N_2O emissions from wastewater treatment, such as dissolved oxygen concentration, nitrite concentration, temperature, COD/N, pH and rapidly changing process conditions [11]. Different from lab-scale experiments, the field experiments in Jinan WWTP found that the operating parameters in large-scale WWTP were relatively stable and could cushion impacts of wastewater flow and quality changes. To determine the main factors influencing N_2O fluxes from this typical large-scale WWTP, a series of water quality parameters were analyzed: pH, temperature, dissolved oxygen concentration, COD, total nitrogen, NH_4^+-N, NO_3^--N and NO_2^--N. The relationships between N_2O fluxes and these parameters were then examined by linear regression techniques.

3.5.1. Dissolved oxygen

The dissolved oxygen concentration was considered to be a very important factor influencing N_2O emissions during nitrification and denitrification processes in wastewater treatment systems [12–14]. In the Jinan WWTP, dissolved oxygen concentration in the anaerobic tanks and anoxic tanks were relatively stable during normal operation, but the DO concentration in oxic tanks occasionally fluctuated due to unstable aeration rates. The oxic tanks were the major nitrous oxide emission contributor, and the DO concentration in this unit was relatively stable and maintained greater than 2 mg L^{-1} under normal operating conditions. Therefore the N_2O flux from this unit was relatively stable under normal operating conditions. During the experimental period, several DO concentration abnormalities (less than 2 mg L^{-1}) were observed in the oxic tanks and the corresponding N_2O fluxes were measured. Investigation indicated that the blower house intentionally decreased the output flow by shutting down

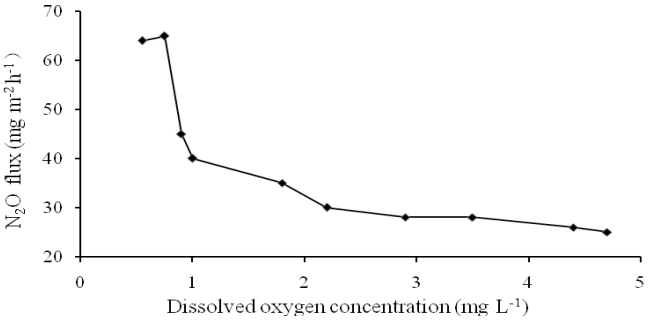

Fig. 4. Relationship between N_2O flux and dissolved oxygen concentration in the oxic tanks.

part of blowers for routine maintenance, which led to the abnormal low DO concentrations in oxic tanks. Because the abnormal situation lasted just for a short time (several hours), mg m^{-2} h^{-1} was used as the unit of N_2O flux from oxic tanks in Fig. 4.

As described in Fig. 4, DO concentration was greater than 2 mg L^{-1} under normal conditions in oxic tanks, and the N_2O fluxes were lower than 30 mg m^{-2} h^{-1} and kept relatively stable. When DO concentration dropped below 2 mg L^{-1}, the N_2O fluxes increased rapidly, and the maximum N_2O flux of 65 mg m^{-2} h^{-1} appeared at DO concentration of 0.75 mg L^{-1}. This variation trends was consistent with Goreau's report [15], because the nitrifier denitrification pathway is held responsible for the rapidly increased N_2O emissions due to dissolved oxygen limitation. The large impact of the DO concentration on N_2O emissions indicated that appropriate aeration control was necessary for the nitrous oxide emission reduction (greenhouse gas mitigation) in the oxic tanks of a large-scale municipal WWTP. In this study, the long-term field measurement found that DO concentration maintained between 4–5 mg L^{-1} could lead to optimal wastewater treatment efficiency and the lowest N_2O fluxes. However, higher DO concentration meant higher aeration rates. In order to save operating costs, the large-scale WWTPs tended to decrease their energy consumption by decreasing aeration rates. So it would be quite difficult to reach the ideal state for the N_2O emission reduction (greenhouse gas mitigation) in full-scale WWTPs at present.

3.5.2. Nitrite concentration

Among various nitrogen forms in wastewater, T-N, NH_4^+-N, NO_3^--N and NO_2^--N, only nitrite concentration was observed to have a significant impact on N_2O flux in this WWTP. Nitrite was known to enhance the N_2O emission during nitrification and denitrification processes [16,17]. In Jinan WWTP, the water quality analyses demonstrated that nitrite concentration in the oxic tanks were low and relatively stable ranging from 0.0015 to 0.015 mg L^{-1}. But occasional fluctuations of nitrite concentration in this unit were observed due to unstable

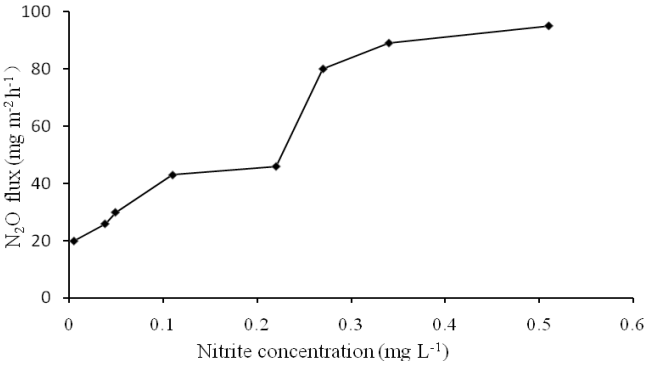

Fig. 5. Relationship between N_2O flux and nitrite concentration in the oxic tanks.

operating conditions, and the measured N_2O fluxes increased with the nitrite concentration. Fig. 5 presents the relationship between nitrite concentration and N_2O fluxes from this unit. Under normal operating conditions, the N_2O^--N concentration in oxic tanks was below 0.1 mg L^{-1}, and the N_2O fluxes (mg m^{-2} h^{-1}) maintained relatively stable. When nitrite concentration increased from 0.22 mg L^{-1} to 0.51 mg L^{-1}, the N_2O fluxes increased rapidly from about 46 mg m^{-2} h^{-1} to 95 mg m^{-2} h^{-1}. The high nitrite concentration during nitrification process in oxic tanks increased denitrification process (effectively nitrite reduction to the intermediate N_2O) by ammonium-oxidizing bacteria, which could elucidate the reason for higher N_2O emissions under these conditions [16].

3.5.3. pH

Studies demonstrated that wastewater pH influenced the N_2O emissions from WWTPs by affecting the biological processes involved in the N_2O production [18,19]. The pH was generally between 6.5 and 7.0 and maintained rather stable in all processing units during the experimental period as the quality and flow of influent wastewater were relatively stable in the Jinan WWTP. The N_2O flux data from each processing unit were examined for pH dependence by linear regression analyses, but no statistically significant correlations ($R^2 < 0.2$) were observed in every processing unit within the experimental range, which meant the pH effect played a minor role in full-scale WWTPs.

3.5.4. Temperature

During the experimental period, wastewater temperature was observed to rise from 12°C to 24°C due to the increase of air temperature. Therefore it was necessary to examine the relationship between N_2O emissions and wastewater temperature. After linear regression analysis, however, no statistically significant correlations ($R^2 < 0.3$) were observed between N_2O emissions and wastewater temperature in the studied processing units.

3.5.5. COD/N

It was reported in several studies that lower or particularly high COD/N ratio could increase the N_2O emissions by influencing denitrification or nitrification processes in wastewater treatment systems [20–24]. Itokawa et al. observed that in an intermittently aerated bioreactor treating high-strength wastewater, 20–30% of the nitrogen load was emitted as N_2O when the influent COD/N ratio was less than 3.5 [21]. In this study, the COD/N ratio was relatively high during nitrification and denitrification processes ranging from 3.6 to 8.7 due to the relatively stable influent water quality and additional organic carbon dosed when limited availability of biodegradable organic carbon was detected. Thus, no statistically significant correlations ($R^2 < 0.2$) were observed between COD/N ratio and N_2O emissions in every processing unit after linear regression analyses.

4. Conclusions

In the Jinan WWTP, the dominant N_2O emission sources were found to be in the following descending order: oxic tanks, final clarifier tanks, anoxic tanks, sludge concentration tanks and anaerobic tanks. The total annual N_2O fluxes from this WWTP ranged from 2.60×10^6 g y^{-1} to 3.29×10^6 g y^{-1}. The emission factors were per capita emissions of 1.73–2.19 g of N_2O $person^{-1}$ y^{-1} and flow based emissions of 2.37×10^{-5} –3.01×10^{-5} g of N_2O (L of wastewater)$^{-1}$. The N_2O emissions accounted for approximately 0.10%–0.13% of the total nitrogen removed in this plant. The estimated N_2O source strength for all China's WWTPs was 0.95–1.20 Gg y^{-1} (1 Gg $=10^9$ g). This can be viewed as an approximation of the order of magnitude of N_2O emissions from China's municipal WWTPs. The operating conditions of the Jinan WWTP were steady during the experimental period due to the relatively stable influent flow and wastewater qualities. Linear regression analyses showed that the main factors influencing N_2O emissions were dissolved oxygen concentration and nitrite concentration in the oxic tanks.

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