2013 Beijing International Environmental Technology Symposium, 20-23 October 2013, University of Science and Technology Beijing, China

Evaluation of Greenhouse Gas Emission from the 7th Wastewater Treatment Plant in Kunming, China

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Abstract: Wastewater treatment plants (WWTPs) is an important source of greenhouse gas (GHG). With the rapid increasing in the numbers of WWTPs and the treatment capacity of wastewater, GHG emission from WWTPs is becoming a seriously environmental problem. By defining the GHG emission boundaries, CO_2 and N_2O emission from biological treatment processes (BOD oxidation, biological nitrogen removal and endogenous respiration), energy consumption, chemical use and sludge disposal were analyzed. The annual amount of GHG emissions from the 7th Kunming WWTP was $63*10^6$ kg CO_2, with the proportions of 64.6% from biological processes, 7.1% from N_2O emission and 24.9% from energy consumption. Secondary wastewater treatment process contributed significantly to total GHG production, with the proportion of 79.2%. Processes of endogenous respiration and N_2O emission should be received much attention so as to better control GHG emission from WWTPs.

Keywords: greenhouse gas; wastewater treatment; nitrous oxide; endogenous respiration; energy consumption

1. INTRODUCTION

In recent years, climate change and global warming have been received intensive attention because of their significant effects on environment, economy and energy (Yerushalmi et al., 2009）. Wastewater treatment plants are considered as an important source of greenhouse gases (GHG), due to the direct or indirect generation of three types of greenhouse gases (GHG), namely carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). CH_4 is usually produced during anaerobic digestion of organic matters. The CH_4 emission rate varies among WWTPs depending on wastewater characteristics, treatment processes, and measurement methods (EI-Fade and Massoud, 2001). CO_2 is usually produced directly from all biological processes, or indirectly from energy consumption and chemical use. N_2O is mainly produced during biological nitrogen removal including nitrification and denitrification (Rassamee et al., 2011). Although the Inter-government Panel on Climate Change (IPCC) states that the N_2O emission from WWTPs is negligible, some researches still consider that the N_2O emission has significant impact on the GHG emissions of WWTPs, due to its high global warming potential of 296 times that of CO_2 (IPCC 2001). According to the IPCC Guidelines, the CO_2 produced during biological processes, which takes part in the natural carbon cycling and does not contribute to global warming, should not be included in the national emission (Gupta, 2012). However, the CO_2 produced during biological process significantly influences the GHG emission from WWTPs (Snip, 2009). Therefore, it is necessary to be included when quantifying the GHG emission of the WWTPs. Lots of studies have focused on the GHG emission from the WWTPs but less on full-scale WWTPs, especially those in China. While with the rapid increase in the numbers of domestic WWTPs and the treatment capacity of wastewater, GHG emissions from domestic WWTPs is becoming a seriously environmental problem in developing countries, including China.

Evaluation of GHG emission from the 7th wastewater treatment plant in Kunming was carried out for biological nutrient removal, energy consumption, chemical usage and sludge disposal. The contribution of each process and key factors affecting the GHG emission were discussed.

2. MATERIALS AND METHODS

2.1 Wastewater treatment plant

The 7th wastewater treatment plant in Kunming was the aerobic/anoxic/aerobic (A^2O) process including both post-denitrification (2/3 of the treated wastewater) and pre-denitrification (1/3 of the treated wastewater). The treatment capacity was 300,000 m^3/d. Coagulation-filtration and ultraviolet disinfection were used as the tertiary treatment for P removal and *E. coli* removal, respectively. Excess sludge was land-filled as the final disposal process. The discharging standard was Class I Grade A of China (SEPAC, 2002). The flow stream of the wastewater treatment plant is shown in Figure 1.

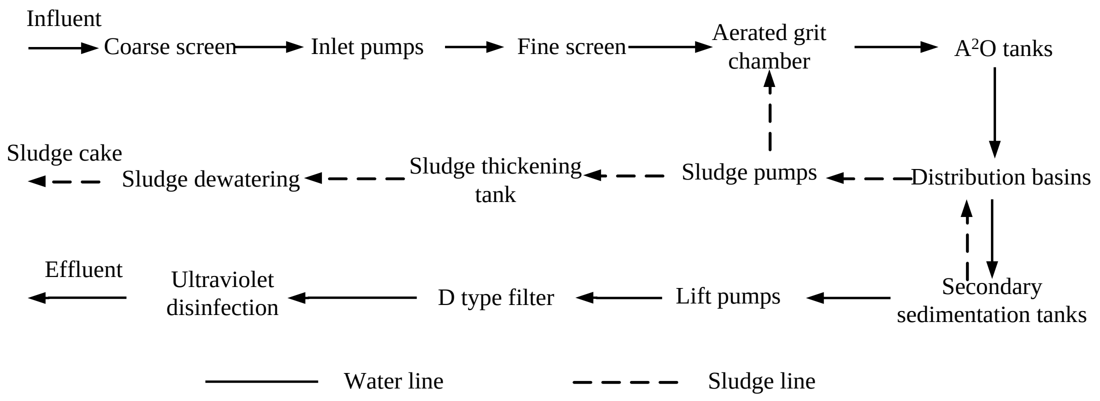

Figure 1. Flow diagram of the 7th wastewater treatment plant in Kunming

Typical parameters for system operation and performance of the 7th wastewater treatment plant in Kunming are given in Table 1.

Table 1. Typical parameters for system operation and performance of the 7th wastewater treatment plant in Kunming

Parameter	**Value**	**Unit**
Influent flow rate	109618333	m^3/yr
Influent BOD	221.4	mg/L
Effluent BOD	1.2	mg/L
BOD removed	23970150	kg/yr
Influent TN	38.1	mg/L
Effluent TN	11.5	mg/L
TN removed	2910028	kg/yr
Influent NH_4-N	22.2	mg/L
Effluent NH_4-N	0.6	mg/L
NH4-N removed	2346631	kg/yr
MLVSS	3426	mg/L
HRT	18	h
Energy consumption	23864597	kWh/yr
Coagulant used	4979259.9	kg/d
Flocculants used	45815	kg/yr
Excess sludge produced	16964455	kg/yr
Distance of sludge transport	32	km

2.2 Analysis boundaries for estimating GHG emissions

A reasonable selection of the analysis boundaries is a prerequisite to estimate the GHG emission of wastewater treatment plants. The selected boundaries in this research was adopted from the Bridle model (Bridle consulting, 2007). According to Bridle model, the boundaries to estimate the GHG emission from the wastewater treatment plants can be grouped as follows: (1) GHG emission from biological processes including endogenous respiration, BOD oxidation, nitrification CO_2 credit and nitrogen removal; (2) Energy consumption; (3) Sludge digestion, such as biogas CH_4 and CO_2; (4) Sludge disposal, such as emissions from transporting sludge to disposal site and CO_2 emission from mineralization; (5) Indirect GHG emission from chemical usage.

There is no anaerobic digestion for sludge or biogas reuse in the 7th waste water treatment plant, so GHG emission of these two processes were not taken into consideration during the calculation. The disposal of excess sludge was landfill after dewatering. Therefore, estimation the GHG emission of sludge processes only included CO_2 production from fuel combustion during sludge transport. The major energy supply of the 7th wastewater treatment plant in Kunming was electricity. Chemical dosage were mainly PAC for phosphorus removal and PAM for sludge dewatering. Based on the above discussion, the boundaries for estimating the GHG emission of the 7th wastewater treatment plant in Kunming included biological treatment processes, energy consumption, chemical usage and sludge transport.

2.3 Calculations of the GHG emission

The GHG emission from biological treatment processes composed of three aspects, the BOD oxidation, nitrogen removal (nitrification and denitrification) and endogenous respiration. Equation (1) was used to estimate the GHG generation during BOD oxidation. Equation (2) was used to estimate the GHG generation during endogenous respiration. Equations (3-1) and (3-2) were used to estimate the CO_2 utilization and N_2O emission during nitrification. With the GWP of N_2O 296 times that of CO_2, the production of N_2O should be converted to the CO_2 equivalent (IPCC, 2001).

$$CO_{2,BODox} = 1.1 \times (\frac{BOD_{ox}}{f_{BOD}} - 1.42 \times X_{net,produced}) \quad (1)$$

$CO_{2,BODox}$ is the CO_2 generation during BOD oxidation (kg), 1.1 is the ration between CO_2 generation and O_2 consumption, BOD_{ox} is the oxidized BOD (kg), f_{BOD} is the ratio between BOD_5 and BOD_u (0.68) (Metcalf and Eddy, 1991), $X_{net,produced}$ is net sludge production per day(kg/day), 1.42 is ratio between COD and MLVSS.

$$CO_{2,decay} = 1.947 \times Q_{in} \times HRT \times MLVSS \times k_d \quad (2)$$

$CO_{2,decay}$ is CO_2 generation during endogenous respiration (kg), 1.947 is the CO_2 production(kg) for the decay of one kg biomass, Q_{in} is the influent flow (m^3/d), HRT is hydraulic retention time, $MLVSS$ is the concentration of mixed liquid volatile suspended solids(kg/m^3), k_d is the endogenous decay coefficient (0.05 1/d) (Snip, 2009).

$$CO_{2,N1} = 4.49 \times [Q_{in} \times (TN_{in} - NH_4 - N_{eff}) \times t - X_{net,produced} \frac{14}{113}] \quad (3\text{-}1)$$

$$CO_{2,N} = 296\times f_N \times[Q_{in}\times(TN_{in} - NH_4 - N_{eff})\times t - X_{net,produced}\frac{14}{113}] \quad (3\text{-}2)$$

$CO_{2,N1}$ is the CO_2 consumed during nitrification (kg), $CO_{2,N2}$ is CO_2 generated during nitrification through the release of N_2O (kg), f_N is the emission factor of N_2O during nitrification(0.005 kg/kg) (IPCC, 2006), 296 is GWP of N_2O, TN_{in} is the concentration of influent TN(kg/m^3), $NH_4 - N_{eff}$ is the concentration of effluent NH_4-N (kg/m^3), t is time (d), $\frac{14}{113}$ is the fraction of nitrogen in biomass.

$$CO_{2,DN} = 296\times f_{DN} \times[Q_{in}\times(TN_{in} - TN_{eff})\times t - X_{net,produced}\frac{14}{113}] \quad (4)$$

$CO_{2,DN}$ is CO_2 emission during denitrification (kg), f_{DN} is emission factor of N_2O during denitrification, TN_{in} is the concentration of influent TN (kg/m^3), TN_{eff} is the concentration of effluent TN (kg/m^3).

The indirect GHG emission from energy consumption, chemical usage and sludge transport were calculated by Equation 5, Equation 6(De Haas et al., 2008) and Equation 7 (De Haas et al., 2008), respectively.

$$CO_{2,e} = kWh\times f_e \quad (5)$$

$CO_{2,e}$ is the CO_2 emission from energy consumption (kg), kWh is energy consumption(kWh), f_e is the CO_2 emission factor of electricity (0.66 kg/ kWh)(Department of Climate change, National Development and Reform Commission http://cdm.ccchina.gov.cn/WebSite/CDM/UpFile/File2975.pdf).

$$CO_{2,chemical} = W_{chemical}\times f_{chemical} \quad (6)$$

$CO_{2,chemical}$ is the CO_2 emission from chemical usage (kg), $W_{chemical}$ is the amount of chemical used (kg), $f_{chemical}$ is the CO_2 emission factor of chemical (1.182 for both PAC and PAM) (De Haas et al., 2008).

$$CO_{2,transport} = L\times f_{fuel}\times f_{transport} \quad (7)$$

$CO_{2,transport}$ is the CO_2 emission from sludge transport (kg), L is the round distance of the plant to the landfill site (km), f_{fuel} is the fuel efficiency of the vehicle (0.554 L/km, De Haas et al., 2008), $f_{transport}$ is the CO_2 emission factor for fuels (2.5 kg CO_2/L for petrol, De Haas et al., 2008).

3. RESULTS AND DISCUSSION

3.1 GHG emissions of WWTP

The calculated GHG emission of the 7th wastewater treatment plant Kunming is shown in Table 2. Biological treatment processes were the greatest sources of the GHG emission, accounting for 64.6% of the total GHG production. Endogenous respiration was the greatest contributor among all biological processes, followed by BOD oxidation and nitrification. There were both N_2O release and CO_2 consumption during the nitrification process and the N_2O release only accounting for 7.1% of all GHG emission. After balancing, it revealed that the nitrification process affected the GHG emission of WWTP slightly with the emission factor of 0.005. Most of the N_2O was released from nitrification process during the biological nutrient removal (Liu et al., 2008), so the N_2O emission from denitrification was excluded from the estimation. The detailed discussion on the influence of the N_2O emission on the total GHG emission is given in Section 3.4. The GHG emission from energy consumption and chemical usage accounted for 24.9% of all GHG emission, among them energy consumption for the aeration accounted for 9.0% GHG emission and PAC consumption for phosphorus removal accounted for 9.3%.

Table 2. Estimation of GHG emission from the 7th wastewater treatment plant in Kunming (the N_2O emission factor during nitrification was 0.005)

		Kg CO_2-e/year	**Percentage**
Total		63252125	
Biological nutrient removal		40863015	64.6%
	BOD oxidation	25526007	40.4%
	Endogenous respiration	24495218	38.7%
	CO_2 credit from nitrification	-13661251	-21.6%
	N_2O emission from nitrification	4503040	7.1%
	N_2O emission from denitrification	0	0
Energy consumption		15750634	24.9%
Chemical usage		5939639	9.4%
	PAC	5885485	9.3%
	PAM	54153	0.1%
Sludge disposal	Sludge transport	698838	1.1%

The total amount of GHG production of the 7th wastewater treatment plant in Kunming was $63*10^6$ $kgCO_2/yr$, or 0.58 kg CO_2/t based on the treated volume of wastewater. Xie obtained the emission ratio of 0.95 kg CO_2/t in A^2O (Xie et al., 2012). The difference was mainly due to the absence of the anaerobic digestion of sludge in the 7th wastewater treatment plant. Based on the research of Keller and Hartle (2003), the contribution of anaerobic digestion of sludge was 0.44 kg CO_2/t, and this value was 0.53 kg CO_2/t in the research of Xie et al. (2012), meanwhile, neither of the two researches above included the GHG emissions from endogenous respiration, while the GHG production from endogenous respiration of the 7th wastewater treatment plant in Kunming was 0.24 kg CO_2/t. The different methods used for assessment was also a factor responsible for the different values obtained. With the unit of CO_2/ kg BOD, the GHG production was 2.64 kg CO_2/kg BOD, which was 20% lower than the value of 3.31 kg CO_2/kg BOD reported by Bani Shahabadi et al. (2009). In this study, the GHG emission from chemical usage only accounted for 9.4% of the total GHG production. Studies included the anaerobic process which would increase the contribution from chemical usage ranged from 6% to 54% (Bani Shahabadi et al., 2009). The production and distribution of GHG varied with treatment processes and emission boundaries. Therefore, it is vital to chose reasonable boundaries according to the practical situation of the WWTPs during estimating of the GHG emission.

3.2 GHG emission along the flow stream of the WWTP

The distribution of GHG emission along the flow stream is shown in Figure 2. The GHG emission from pretreatment, secondary treatment, tertiary treatment and sludge disposal processes were 4.9%, 79.2%, 13.4% and 2.5% of the total GHG emission, respectively. The secondary treatment process was the largest emission source of GHG in the 7th wastewater treatment plant because most WWTPs in China used biological nutrient removal processes to achieve the discharging standard.

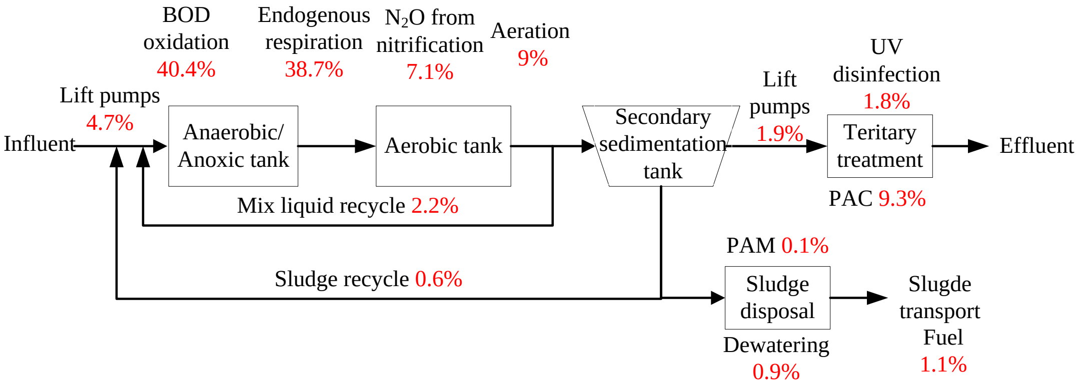

Figure 2. Distribution of GHG emissions along the flow stream

The electricity consumption of the inlet pumps contributed significantly to the GHG emission from the pretreatment process. The GHG emission from pretreatment process can be reduced by operation optimization and variable frequency control of the pumps to make the pumps working more efficient and energy-saving. Biological processes and energy consumption both led to GHG emission during biological nutrient removal, so we should synthesize the two aspects while considering the reducing GHG emission during secondary treatment. Relating to the biological nutrient removal process, the BOD oxidation is inevitable so the focus of emissions control should be endogenous respiration and N_2O release. Energy consumption can be significantly reduced through DO control during the aeration (Rieger, 2012), resulting in the reduced GHG emission. Through the optimization of biological phosphorus removal, the GHG emission from chemical usage for phosphorus removal could be reduced.

3.3 Effect of endogenous respiration on GHG emissions

As stated above, the GHG emission from endogenous respiration accounted for a large part of the total GHG emission. The GHG emission from endogenous respiration increased sharply with the increase in the decay rate (shown in Figure 3). When the decay rate increased from 0.01 to 0.1 1/d, the proportion of GHG emission generated by endogenous respiration increased from 11.2% to 55.8%, illustrating that GHG emission from endogenous respiration had significant effects on total amount of GHG emission.

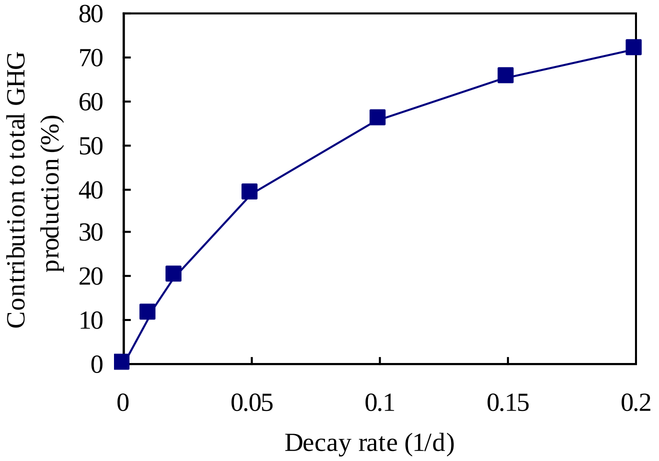

Figure 3. Effect of endogenous respiration on GHG emissions under different decay rate

For wastewater treatment plants, sludge retention time (SRT) is an important controlling factor and is closely related to the decay rate of biomass. With increasing of SRT, more biomass will experience endogenous respiration (Salem et al., 2006). Therefore, a long SRT is inappropriate for GHG emission reduction. However, a longer SRT may reduce the sludge production of systems. Sludge disposal has become a serious problem, and some WWTPs tend to operate at a long SRT to reduce sludge production. Meanwhile, a long SRT is key factor to ensure effective nitrification and reduce the N_2O release from denitrification (Zheng et al., 1994; Hanaki et al., 1992). The effects of the long SRT operating mode of the WWTPs should be balanced among the quality of effluent wastewater, sludge reduction and GHG emission to make the WWTPs more environmental sustainable.

3.4 Effect of N_2O on GHG emission

Contribution of N_2O emission to the total GHG production under different emission factors and different processes (only nitrification, only denitrification and both nitrification and denitrification) was discussed, with results shown in Figure 4.

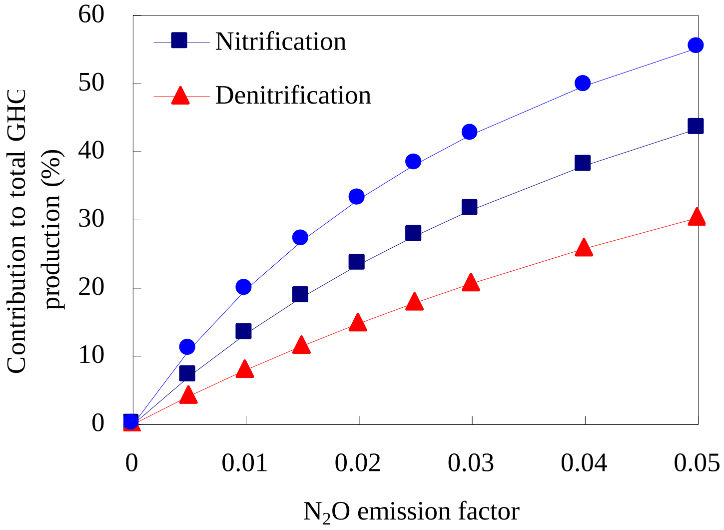

Figure 4. Effect of N_2O on GHG emissions under different N_2O factor

Generally, most of the wastewater treatment plants have good nitrification performance, with the removal efficiency of NH_4-N higher than the removal efficiency of TN. The N_2O emission factor during nitrification significantly affected the contribution of N_2O emission to the total GHG production. According to the research of Kampschreur et al. (2009), there was 0-95% of the nitrogen load emitted as N_2O in lab-scale systems and 0-14.6%.in full-scale systems. As shown in Figure 4, with the increasing of N_2O emission factor, the contribution of N_2O emission to the total GHG production increased sharply. The N_2O emission of WWTPs needed to be more focused and better controlled. Because more than 90% of NH_4-N and 65% of TN was removed during wastewater treatment process, it was inadequate to include only the N_2O emission from the effluent as recommended by IPCC (IPCC, 2006). Measures for controlling N_2O emission mainly includes: maintaining appropriate DO concentration in biological system, avoiding NO_2-N accumulation and providing sufficient carbon source for during denitrification, etc.

3.5 Effect of energy consumption on GHG emission

The distribution of GHG emission due to energy consumption was consistent with the distribution of energy consumption. Figure 5 presented the distribution of energy consumption of the 7th wastewater treatment plant in Kunming. The main energy-consuming equipments were air blowers and pumps, which contributed to 62% of the total energy consumption. By energy saving of the main energy-consuming equipments, it will reduce the GHG emission from energy consumption. However, the GHG emission from energy consumption only accounted for 24.9% of the total GHG emission of the WWTP and it slightly affected the total GHG reduction. For example, even with the energy consumption reduced by 20%, there was only 4.9% total GHG reduction. Therefore, energy saving was not a major approach to reduce GHG emission but could save the operation cost of WWTPs.

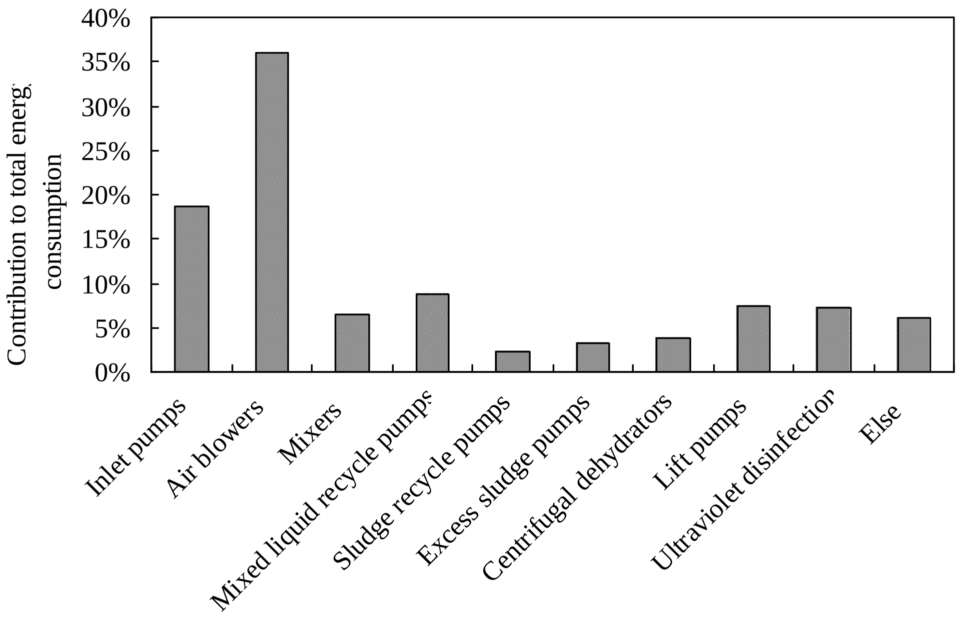

Figure 5. Distribution of GHG emission from energy consumption

4. CONCLUSIONS

GHG emissions from biological treatment process, chemicals usage, energy consumption and sludge disposal were evaluated for the full-scale 7th wastewater treatment plant in Kunming, China. The follows were obtained.

(1) The GHG production of 7th wastewater treatment plant in Kunming was $63*10^6$ $kgCO_2/yr$, with the contribution from biological processes, N_2O emission and energy consumption of 64.6%, 7.1% and 24.9%, respectively.

(2) Endogenous respiration and N_2O emission had significant effects on the total GHG emission, and these two processes needed to be further examined.

(3 Energy saving reduced the operating cost of WWTPs but only slightly affected the total GHG emission.

5. ACKNOWLEDGEMENTS

This research is supported by the Major Science and Technology Program for Water Pollution Control and Treatment of China (2012ZX07302002), the Seed Funding of Graduate School at Shenzhen, Tsinghua University (ZJ20110004) and Shenzhen Science and Technology Development Funding-Fundamental Research Plan (No. JC201006030878A).

REFERENCES

Bani Shahabadi, M., Yerushalmi, L. & Haghighat, F. 2009 Impact of process design on greenhouse gas (GHG) generation by wastewater treatment plants. Water Research, 43(10), 2679-2687.

Bridle Consulting. 2007 Development of a process model to predict GHG emissions from the water corporation metropolitan WWTPs.

De Haas, D., Foley, J. & Barr, K. 2008 Greenhouse gas inventories from WWTPs the trade off with nutrient removal. Proceedings of the Water Environment Federation, Sustainability 2008, 264-295.

Diksha, G. & Santosh, K.S. 2012 Greenhouse gas emissions from wastewater treatment plants: a case study of Noida. Journal of Water Sustainability, 2(2), 131-139.

Department of Climate change, National Development and Reform Commission.http://cdm.ccchina.gov.cn/WebSite/CDM/UpFile/File2975.pdf (In Chinese)

EI-Fadel, M. & Massoud, M. 2001 Methane emission from wastewater management. Environmental Pollution, 114(2), 117-185.

Hanaki, K., Hong, Z. & Matsuo, T. 1992 Production of nitrous oxide gas during denitrification of wastewater. Water Science and Technology, 26(5-6), 1027-1036.

IPCC. 2001 Climate change 2001: the scientific basis. Cambridge: Cambridge University Press, UK.

IPCC. 2006 2006 IPCC guidelines for national greenhouse gas inventories. IGES, Japan.

Kampschreur, M.J., Temmink, H., Kleerebezem, R., Jetten, M.S.M. & Van Loosdrecht, M.C.M. 2009 Nitrous oxide emission during wastewater treatment. Water Research, 43, 4093-4103.

Keller, J. & Hartley, K. 2003 Greenhouse gas production in wastewater treatment: process selection is the major factor. Water Science and Technology, 47(12), 43-48.

Liu, X., Peng, Y., Wu, C., Akio, T. & Peng, Y. 2008 Nitrous oxide production during nitrogen removal from domestic wastewater in lab-scale sequencing batch reactor. Journal of Environmental Sciences, 20, 641-645.

Metcalf & Eddy. 1991 Wastewater engineering: treatment, disposal, reuse. McGraw-Hill: Toronto, Ontario, Canada.

Monteith, H.D., Sahely, H.R., MacLean, H.L. & Bagley, D.M. 2005 A rational procedure for estimation of greenhouse-gas emissions from municipal wastewater treatment plants. Water Environment Research, 77, 390-403.

Rassamee, V., Sattayatewa, C., Pagilla, K. & Chandran, K. 2011 Effect of oxic and anoxic conditions on nitrous oxide emissions from nitrification and denitrification processes, Biotechnology and Bioengineering, 108, 2036-2045.

Rieger, L., Takacs, I. & Siegrist, H. 2012 Improving nutrient removal while reducing energy use at three Swiss WWTPs using advanced control. Water Environment Research, 84(2), 170-188.

Salem, S., Moussa, M.S. & Van Loosdrecht, M.C.M. 2006 Determination of the decay rate of nitrifying bacteria. Biotechnology and Bioengineering, 94(2), 252-262.

Snip, L.J.P. 2009 Quantifying the green house gas emissions of wastewater treatment plants. Wageningen University.

State Environmental Protection Agency of China (SEPAC). 2002 Discharge Standard of Pollutants for Municipal Wastewater Plant (in China)-GB18918-2002.

Yerushalmi, L., Haghighat, F. & Shahabadi, M.B. 2009 Contribution of onsite and offsite processes to greenhouse gas emissions (GHG) by wastewater treatment plants. World Academy of Science, Engineering and Technology, 54, 618-622.

Zheng, H., Hanaki, K. & Matsuo, T. 1994 Production of nitrous oxide gas during nitrification of wastewater. Water Science and Technology, 30(6), 133-141.

Xie, T. & Wang, C. 2012 Greenhouse gas emissions from wastewater treatment plants. Journal of Tsinghua University (Science & Technology). 52(4), 473-477. (In Chinese)