Greenhouse Gas Emissions Evaluations of Wastewater Treatment Plant—A Case Study of Jiaxing, China

Shaoyi Wang, Shengsheng Han, Zelong Qu, Lijun Wu, Jian Yu, Yifan Lou, Hailan Yu, Huabin Shentu, Senjun Huang, and Jun Wei

Abstract This paper provides a comprehensive analysis of greenhouse gas (GHG) emissions associated with a wastewater treatment plant in Jiaxing, China. The study calculated scope 1–3 GHG emissions for all stages of the wastewater treatment system. The study evaluated the sources of GHG emissions and identified opportunities for reducing emissions in the wastewater treatment plant. The results show that the carbon emissions of each stage vary based on the power consumption and the associated emission factors. The study recommends the use of renewable energy sources, energy-efficient technologies, and green supply chain management practices to reduce carbon emissions. The study highlights the significance of considering indirect emissions such as scope 2 and scope 3 emissions to provide a more comprehensive estimate of a facility's carbon footprint. The findings align with previous studies that have emphasized the importance of reducing energy consumption and adopting sustainable practices to improve the sustainability of wastewater treatment plants.

Keywords Greenhouse gas emission · Wastewater treatment · Carbon emission

S. Wang · H. Yu · J. Wei (✉)
Huadong Eco-Environmental Engineering Research Institute of Zhejiang Province, Hangzhou 311122, Zhejiang, China
e-mail: Wei_j2022@126.com

S. Han · Z. Qu · L. Wu · H. Shentu · S. Huang
Department of Ecology and Environment, PowerChina Huadong Engineering Corporation Limited, Hangzhou 311122, Zhejiang, China

Y. Lou
Jiaxing United Sewage Treatment Cooperation Limited, Jiaxing 314002, Zhejiang, China

J. Yu
College of Environment, Hohai University, Nanjing 210024, China

1   Introduction

Global warming is a rising concern in the past few decades. China had pledged to reach its CO_2 emissions peak before 2030 and attain carbon neutrality by 2060 in order to lessen the effects of climate change. This objective drives the Chinese government's efforts to find solutions to lower the greenhouse gas (GHG) emissions produced by all sectors of the economy. Urban water systems are responsible for 1–3% of the nation's GHG emissions [1]. Though the percentage is low, for individual cities with high population, the absolute amount of GHG emission by water system is not to be disregarded [2]. According to the data from National Bureau of Statistics of China (NBS), 575 million people in China lives in urban areas by the year 2020, consuming 581 billion cubic meters of water, and produce 94.6 million tons of CO_2, which is approximately equivalent to the total CO_2 emissions of Columbia in 2020 [3]. The number is still increasing as the total population grows.

Many different evaluation methods have been reported to estimate the GHG emissions of water systems at all stages. The most commonly agreed methodologies to estimate national GHG emission are the *2006 IPCC guidelines for National Greenhouse Gas Inventories* [4]. Besides, the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) released the *GHG Protocol Corporate Accounting and Reporting Standard* to provide guidance on GHG accounting in various industries. It introduced three scopes of GHG emission: scope 1 emissions refer to the direct GHG emissions that result from sources that the entity owns or controls; scope 2 emissions are indirect GHG emissions that result from electricity and heat power that the entity purchases and consumes; scope 3 emissions are all other indirect GHG emissions that result from the entity's operations but come from sources not owned or controlled by the entity.

According to the previous studies, many factors affecting the GHG emissions of wastewater systems including: energy use (diesel, coal, gas, electricity, solar power, etc.), local electrical grid, treatment process, etc. [2, 5]. Therefore, the reported GHG emissions of wastewater systems of different cities varied greatly worldwide. Saidan et al. [6] presented a baseline assessment of carbon emission in water utilities in Madaba, Jordan using Energy performance and Carbon Emissions Assessment and Monitoring tool (ECAM tool), the result showed that the energy consumed by the entire water system in Madaba releases 28.122 thousand tons of CO_2 per year, where the water supply system consumed 89.7% of the energy, whereas the wastewater system consumed only 10.3% of the energy [6]. Racoviceanu et al. [7] estimated the life cycle energy use and GHG emissions for water supply system in Toranto, Canada. It was found that the average carbon emission intensity was 0.144 ~ 0.576 kgCO_2/m^3, depending on the electrical grid used [7]. Another study by Ma et al. [8] found that the carbon emission of China's urban water supply system was 0.377 kgCO_2/m^3. The number was positively related with the economic patterns as it is higher in eastern coastal areas of China than it was in western regions [8]. A study by Zhang et al. [2] reveals that power use is the greatest source of GHG emissions in drinking water services, while in the wastewater system, non-CO_2 emissions sometimes can

be significant, depending on the various regional contexts and wastewater treatment technology.

This study presents a systematic calculation of the GHG emissions of wastewater treatment plant in Jiaxing, China. The scope 1–3 GHG emissions were calculated for all stages wastewater treatment system. The results of GHG emission were presented using CO_2-eq. The study will provide a comprehensive view on the source of GHG emissions associated with wastewater treatment plant, as well as additional guidance on GHG reduction opportunities for the wastewater treatment plant.

2 Material and Methods

The Jiaxing United Sewage Treatment Co., Ltd. (hereinafter referred to as "United Sewage") was established in April 2000 and is mainly responsible for the collection, transportation, treatment, and discharge of industrial and domestic wastewater in Jiaxing city (except Tongxiang and Haining). The service area covers more than 1860 km^2 and serves a population of about 2.5 million people. The company has one sewage treatment plant with a processing capacity of 600,000 tons/day, 200 km of transmission pipelines, and 20 transmission lift stations.

Carbon emissions of United Sewage mainly include indirect emissions generated by drug consumption, pump stations, and equipment power consumption, and direct emissions generated by wastewater biological treatment. In this study, the carbon emissions and emission efficiency of each process stage were calculated based on the electricity consumption, drug consumption, and effluent quality of each process stage according to the sewage treatment process of the plant. The process flowchart of the United Sewage Treatment Plant is shown in Fig. 1. For convenience of calculation, the treatment process is divided into three stages, namely (1) pretreatment; (2) oxidation ditch + AAO + MBR; (3) deep treatment; (4) sludge treatment.
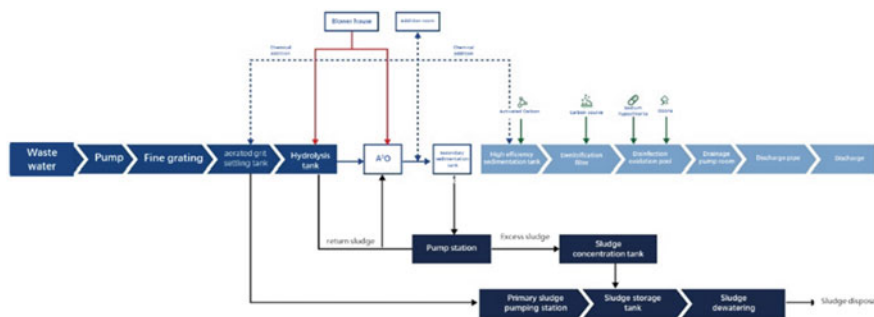

Fig. 1 Water treatment process of the united sewage treatment plant

Wastewater treatment process involves the direct GHG emissions (scope 1), consumption of electricity (scope 2) and chemicals (scope 3). The direct GHG emissions mainly include CH_4, N_2O, and CO_2. The emission of CH_4 is usually generated during the anaerobic digestion process, and it can be calculated as follows:

$$C_{CH_4} = P \times D_{dom} \times B_0 \times MCF - R \qquad (1)$$

where P is the population which is serviced by the wastewater treatment plant, D_{dom} the per capita annual BOD discharge; B_0 the maximum potential for CH_4 production; MCF the modifying factors and R the volume of recovery CH_4.

In the aerated zones of wastewater treatment, the nitrogen is removed from the system by both nitrification and denitrification reactions, releasing N_2O into the atmosphere. The emission of N_2O is difficult to be quantified by stoichiometry, so empirical conversion rate is required to calculate the emission:

$$C_{N_2O} = Q \times (TNe - TNo) \times EFNi \times 10^{-3} \times GWP(N_2O) \qquad (2)$$

where Q is the total inflow of plants, TNe is the total nitrogen of inflow water, []; TNo is the total nitrogen of effluent water, EFNi is the N_2O–N emission factor of denitrification process and the $GWP(N_2O)$ is the global warming potential of N_2O which is taken value as 265 from the 2019 IPCC guidelines.

There are two sources of CO_2 emissions in wastewater treatment process, one is generated by aerobic decomposition of organic matter, and the other is caused by the microbial endogenous respiration and metabolism, described as follows:

$$C_{CO_2,a} = 1.62Q \times \left(BOD_{e,a} - BOD_{o,a}\right) \times 10^{-3} - 1.56yY_tQ\left(BOD_{e,a} - BOD_{o,a}\right) \times 10^{-3} \qquad (3)$$

$$C_{CO_2,M} = 1.947Q \times HRT_a \times MLVSS_a \times K_0 \times 10^{-3} \qquad (4)$$

$$K_0 = Kd_{20} \times (\theta_T)^{T-20} \qquad (5)$$

where Q is the total inflow of plants; $BOD_{e,a}$ is the BOD of inflow water; $BOD_{o,a}$ is the BOD of effluent water; y is proportion of MLVSS in MLSS; Y_t is total sludge yield coefficient, unit kgMLSS/kgBOD$_5$. Q is the total inflow of plants; HRT_a is the hydraulic retention time of aerobic zone; MLVSSa is the MLVSS in the aerobic zone; K_0 is the attenuation coefficient. Kd_{20} is the attenuation coefficient under 20 °C circumstance, and the study takes 0.04; θ_T is the temperature coefficient, value 1.03; T is the design temperature.

Due to the availability of total sludge yield coefficient, the study use the default value from Wang's study [3]. What's more, greenhouse gas emissions caused by this process are caused by biological catabolism, and the organic carbon degraded in this part is not fossil carbon.

During the water treatment process, the indirect GHG emission is caused by both electricity consumption (scope 2) and the chemical consumption (scope 3), expressed as:

$$W_{WM-E} = P \times EF_{CO_2} \tag{6}$$

$$W_{WM-C} = M_{al} \times EF_{al} + M_{cl} \times EF_{cl} + M_{pp} \times EF_{pp} \tag{7}$$

where W_{WM} is the carbon emission of water treatment, $[M]$; P is the consumption of electricity, $[W]$; M_{al} is the consumption of alums, $[M]$; EF_{al} is the carbon emission factor of alums; M_{cl} is the consumption of chlorine, $[M]$; EF_{cl} is the carbon emission factor of chlorine; M_{pp} is the consumption of potassium permanganate, $[M]$; EF_{pp} is the carbon emission factor of potassium permanganate.

3 Results

In this wastewater treatment plant, the wastewater will be treated by the A_2O biological pool, denitrification deep bed filter, and membrane bio-reactor. So the study also calculates the N_2O emission of the denitrification and the CO_2 emission of aerobic decomposition and microbial endogenous respiration besides the carbon emission of wastewater collection and sludge treatment.

3.1 Wastewater Treatment

Direct carbon emission (scope 1)

The result of direct carbon emissions is calculated according to Eqs. (1–5). The calculated result is given in Table 1. In a word, the total direct carbon emission is 2.66×10^4 tCO_2. The carbon emission of aerobic decomposition takes 65.39% of the total carbon emission. The N_2O emission accounts for 34.56% of the total emission. The emission of microbial endogenous respiration is least part, taking only 0.05% of total emission.

Table 1 Direct carbon emission for wastewater treatment system

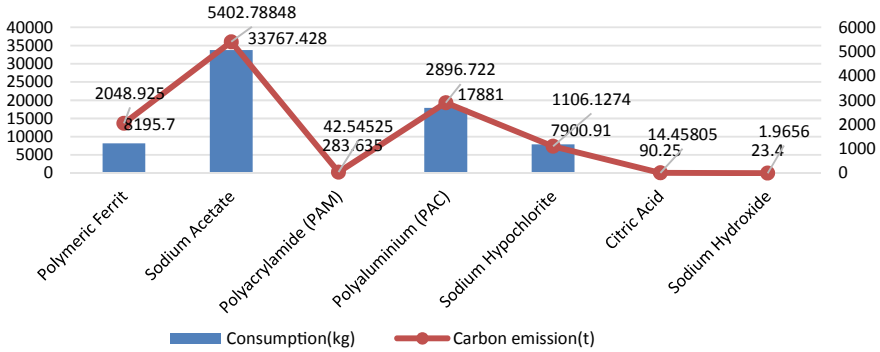| N_2O emission (tCO_2-eq)	Carbon emission of aerobic decomposition (tCO_2)	Carbon emission of microbial endogenous respiration (tCO_2)	Total direct carbon emission (tCO_2)
9.19×10^3	1.74×10^4	13.42	2.66×10^4

Fig. 2 Carbon emission of agenda consumption

Indirect carbon emission (Scope 2 and scope 3)

The scope 2 carbon emission includes the consumption of agent and electricity. Firstly, the emission of agent consumption is calculated according to Eq. (7). The consumptions of polymeric ferrit, sodium acetate, polyacrylamide (PAM), polyaluminium (PAC), sodium hypochlorite, citric acid, and sodium hydroxide are 8.20×10^6, 3.38×10^7, 2.84×10^5, 1.79×10^7, 7.90×10^6, 9.03×10^4, and 2.34×10^4 kg according to the record provided by the United Sewage. The calculated results are shown in Fig. 2.

The consumption of various agents has resulted in a total carbon emission of 1.15×10^4 tCO_2. Sodium acetate contributes to the majority of this emission, accounting for 44.3% (5.40×10^3 tCO_2) due to its extensive use. The emission caused by PAC accounts for 25.16% of the total emission, while the combined emissions of PAM, citric acid, and sodium hydroxide only amount to 0.52% of the total.

Furthermore, indirect carbon emissions arise from electricity consumption. In this study, we obtained data on the electricity consumption of wastewater treatment equipment from a reliable source. Using Eqs. (8–9), the total electricity consumption of 6.19×10^7 kWh is divided by the volume of sewage treated ($1.90 \times 10^8 m^3$), resulting in an energy intensity of 0.33kWh/m3. The total amount of CO_2 emission is 4.90×10^4 tCO_2.

3.2 Sludge Treatment

In the wastewater treatment process, a substantial amount of sludge is generated annually, totaling approximately 1.76×10^5 t per year. The sludge is collected, pumped into a storage tank, dewatered, and then sent to three different refuse incineration plants for disposal. The agent consumption during the sludge dewatering process includes lime (11.4 kg/t), polyacrylamide (0.97 kg/t), and ferric chloride (11.50 kg/

t). The total carbon emissions resulting from these processes were calculated to be 5.279×10^3 tCO$_2$-eq, which is equivalent to 29.94 kg CO$_2$-eq per ton of sludge.

The electricity consumption associated with the dewatering process is another important factor to consider. This includes the pumps (5.26 kWh/t) and the centrifuge dewatering machine (5.26 kWh/t). The total carbon emissions resulting from electricity consumption were estimated to be 2.587×10^3 tCO$_2$-eq, or 29.94 kg CO$_2$-eq per ton of sludge.

4 Discussion

Only two levels of headings should be numbered. Lower level headings remain unnumbered; they are formatted as run-in headings.

Table 2 gives the carbon emission of wastewater treatment process at different stages. The findings suggest that there is a significant variation in the carbon emissions of different stages, which can be attributed to the energy consumption and the types of emissions associated with each stage. Our results are consistent with the previous studies that have reported the importance of wastewater treatment processes in reducing carbon emissions and mitigating the impact of climate change [2].

The study examined the carbon emissions and energy consumption of different stages in wastewater treatment plants. The pretreatment stage was found to have the lowest power consumption and carbon emissions, with only 1.96% of total carbon emissions. The low carbon emissions of the pretreatment stage can be attributed to the water inlet pump and agent consumption. These findings are consistent with Svardal and Kroiss's (2011) study, which reported that the pretreatment stage has low energy requirements and produces fewer greenhouse gas emissions [9].

On the other hand, the oxidation AAO + secondary oxidation stage had the highest carbon emissions due to its high power consumption and large amount of agent

Table 2 Carbon emissions of wastewater treatment process at different stages

Treatment unit	Power consumption (kWh/m3)	Carbon emission (kgCO$_2$-eq/t)	SCOPE1	SCOPE2	SCOPE3	Total carbon emission (tCO$_2$-eq)
Pretreatment	0.03	0.02	0.00	2140.77	0.00	2140.77
AAO + secondary oxidation	0.26	0.66	9519.26	19,373.26	32,168.41	61,060.93
Denitrification + Disinfection	0.36	0.40	0.00	27,058.40	10,904.34	37,962.74
Sludge dewatering	18.52	44.62	0.00	2587.53	5279.90	7867.43
Sum	19.18	45.70	9519.26	51,159.95	48,352.65	109,031.87

consumption. Liao et al. (2020) reported that energy consumption in the biological treatment stage is a significant contributor to carbon emissions [10]. Thus, the optimization of energy consumption in the biological treatment stage can help reduce carbon emissions.

The denitrification + disinfection stage was found to have high scope 2 emissions, consistent with He et al.'s (2018) study. The electricity consumption of the denitrification stage is a significant contributor to indirect carbon emissions. However, alternative processes like biological nitrogen removal through oxygenic denitrification can help reduce energy consumption [11].

The sludge dewatering stage was found to have the highest power consumption, which is consistent with Chen and Kuo's [12] findings. The authors reported that the sludge dewatering stage is the most energy-intensive process in wastewater treatment plants and significantly contributes to greenhouse gas emissions [12]. Thus, the implementation of energy-efficient technologies and the recovery of energy from sludge can help reduce the carbon emissions of this stage.

5 Conclusion

The wastewater treatment plant emitted 109,031.87 tCO_2, with scope 2 emissions being the highest due to electricity consumption, accounting for 35.81%. Sludge dewatering and incineration had the highest carbon emissions per ton at 236.46 kg CO_2-eq/t. The carbon emissions of each process were analyzed, with biological treatment in the first and second phases being the highest. The carbon emissions in the first phase were mainly due to drug agents in scope 3, accounting for 52.01%, while electricity consumption accounted for 28.34%. In the second phase, the carbon emissions of AAO were also dominated by scope 3, accounting for 53.12%, while electricity consumption accounted for 33%.

In conclusion, the findings of this study highlight the importance of wastewater treatment processes in reducing carbon emissions and mitigating the impact of climate change. Companies can adopt energy-efficient technologies and renewable energy sources to reduce their carbon emissions and contribute to a sustainable environment. Further research is needed to investigate the potential of carbon capture and utilization technologies in wastewater treatment plants to reduce carbon emissions.

References

1. Zhang B, Chen ZM, Qiao H, Chen B, Hayat T, Alsaedi A (2015) China's non-CO2 greenhouse gas emissions: inventory and input–output analysis. Eco Inform 26:101–110
2. Zhang Q, Smith K, Zhao X, Jin X, Wang S, Shen J, Ren ZJ (2021) Greenhouse gas emissions associated with urban water infrastructure: what we have learnt from China's practice. WIREs Water 8:e1529
3. NBS (2021) China statistical yearbook 2021. National Bureau of Statistics of China, Beijing

4. IPCC (2006) IPCC guidelines for national greenhouse gas inventories. Institute for global environmental stratigies, Japan
5. Anthony HJ, Tanju K (2013) Calculating the greenhouse gas emissions of water utilities. J (Am Water Works Assoc) 105:E363–E371
6. Saidan M, Khasawneh HJ, Aboelnga H, Meric S, Kalavrouziotis I, Jasem ASH, Hayek BO, Al-Momany S, Al Malla M, Porro JC (2019) Baseline carbon emission assessment in water utilities in Jordan using ECAM tool. J Water Supply: Res Technol-Aqua 68:460–473
7. Racoviceanu AI, Karney BW, Kennedy CA, Colombo AF (2007) Life-cycle energy use and greenhouse gas emissions inventory for water treatment systems. J Infrastruct Syst 13:261–270
8. Ma J, Yin Z, Cai J (2022) Efficiency of urban water supply under carbon emission constraints in China. Sustain Cities Soc 85:104040
9. Svardal K, Kroiss H (2011) Energy requirements for waste water treatment. Water Sci Technol 64:1355–1361
10. Liao X, Tian Y, Gan Y, Ji J (2020) Quantifying urban wastewater treatment sector's greenhouse gas emissions using a hybrid life cycle analysis method—an application on Shenzhen city in China. Sci Total Environ 745:141176
11. He Z, Feng Y, Zhang S, Wang X, Wu S, Pan X (2018) Oxygenic denitrification for nitrogen removal with less greenhouse gas emissions: microbiology and potential applications. Sci Total Environ 621:453–464
12. Chen Y-C, Kuo J (2016) Potential of greenhouse gas emissions from sewage sludge management: a case study of Taiwan. J Clean Prod 129:196–201