Exploring the impact of hyper-quantity on the performance to access GHG emission in a full-scale A 2 O+MBR process: From predictions to implementation

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Abstract

It was different to reduce the greenhouse gas (GHG) emission intensity of the wastewater treatment industry in China, owing to a lack of research and demonstration experience. This study aims to predict hyper-quantity functional performance, and provide a guidance for its real operation to assess the GHG emission in a full-scale anaerobic-anoxic-oxic membrane bioreactor (A2O + MBR) process in Beijing. The emulated result illustrated that ASM model offers broad applicability to predict functional performance during hyper-quantity operational periods. The running results show that the GHG emission intensity decreased from 1.31 CO₂e/m³ to 1.24 CO₂e/m³, representing a 5.3% decline in 2022, despite the total annual GHG emissions increased by 42.69% compared to the levels in 2018. Further, the GHG emission intensity of CH₄, N₂O, electricity consumption and chemical agent consumption decreased by 7.4%, 7.1%, 4.9% and 12.5%, respectively. The proportion of CH₄, N₂O, electricity and chemical agent consumption accounted for 20.38%, 31.89%, 47.67% and 0.06% of the total GHG emissions, showing minimal changes compared to those in 2018. Overall, this research provides valuable insights to policy-makers regarding water and carbon issue, assisting them in identifying to find low-risk and cost-effective solutions to reduce climate change impact.

Highlights

A full-scale A²O+MBR process is emulated to predict hyper-quantity functional performance, and instruct its operation.

The real operation of the process suggests that hyper-quantity operation leads to a decrease in GHG emission intensity.

Through sensitivity analysis, we identify a range of treated quantities that lead to an increase and decrease in GHG emission intensity.

The study provides a valuable example for other similar wastewater treatment systems to decrease GHG emission intensity.

1. Introduction

Wastewater treatment plants (WWTPs) have been recognized as one of the largest energy consumers and greenhouse gas (GHG) emitters in urban systems (IPCC. 2021). The shares of global energy use and GHG emissions from WWTPs are expected to increase in the coming year, due to rapid urbanization and the implementation of more rigorous water quality regulations for reclaimed water in China (Li et al. 2015). Enhancing denitrification efficiency often requires further addition of carbon sources. The P removal relies heavily on dephosphorization agents to achieve the requires the discharge limits, especially during periods of enhanced biological phosphorus removal (EBPR) upset that often occur in summer (Hu et al. 2023, Liu et al. 2011, Santos et al. 2020). These additional measures enhanced the
GHG emissions and intensity (Santos et al. 2020). In this regard, Hu et al. (Hu et al. 2021) founded that the GHG emission intensity in a reclaimed WWTP utilizing a full-scale A\textsuperscript{2}O + MBR process in Beijing was measured to be 1.31 kgCO\textsubscript{2}e/m\textsuperscript{3} (CO\textsubscript{2}-equiv/m\textsuperscript{3} of wastewater). However, Singh et al. (Singh & Kansal 2018) reported that the average GHG emission intensity was found to be 0.78 kgCO\textsubscript{2}e/m\textsuperscript{3} (CO\textsubscript{2}e/m\textsuperscript{3}) for large-scale WWTPs and 3.04 kgCO\textsubscript{2}e/m\textsuperscript{3} for small-scale WWTPs. Furthermore, the GHG emissions intensity in large-scale WWTPs in Zhengzhou China was measured to be 1.06 kgCO\textsubscript{2}e/m\textsuperscript{3} with fugitive emissions accounting for more than 70% of the total carbon emissions, as reported by Yu et al. (Yu et al. 2020).

To dates, numerous reports have primarily focused on optimizing individual processes and estimating GHG emissions from wastewater treatment system. The BioWin software based on ASM2d offers broad applicability for the simulating of process simulation to optimize individual processes, such as A/O, A\textsuperscript{2}/O, MBR, and so forth (Hu et al. 2003, Machado et al. 2014, Sun et al. 2016). In addition, Su et al. (Su et al. 2023) updated the Computable General Equilibrium-based System Dynamics and Water Environmental Model (CGE-SyDWEM), which was a recently developed model that simulating the water-energy-carbon nexus at the watershed level. This model was used to calculate both the direct and indirect GHG emissions from integrated urban drainage systems (IUDSs) considering carbon mitigation strategies and water engineering practices. In another study, Shrestha et al. (Shrestha et al. 2022) employed Python programming to estimate the GHGs emissions originating from the domestic wastewater sector in Nepal. They assessed multiple technological development scenarios spanning from 2020 to 2040 using the refined estimation methodology developed by Inter-governmental Panel on Climate Change (IPCC) in 2019 (IPCC. 2021). Shuhei Masuda et al. (Masuda et al. 2018) studied the GHG emissions from different sewage treatment plants, including those using the oxidation ditch process, double-circulated anoxic-oxic process. Their survey revealed that if the discharge of dissolved nitrous oxide discharge is not taken into account, nearly 7% to 14% of total nitrous oxide emission would be overlooked. In another investigation, Chang et al. (Chang et al. 2017) examined that the energy consumptions and associated GHG emissions in operational phases of urban water reuse systems in Korea. They found that the average total energy consumption and the corresponding GHG emissions of the conventional process were calculated to be 0.511 kWh/m\textsuperscript{3} and 0.43 kgCO\textsubscript{2}e/m\textsuperscript{3}, respectively. In contrast, centralized wastewater reuse systems exhibited higher energy consumptions levels ranging from 1.224 kgCO\textsubscript{2}e/m\textsuperscript{3} to 1.914 kWh/m\textsuperscript{3} and GHG emissions from 0.72 kgCO\textsubscript{2}e/m\textsuperscript{3} to 0.83 kgCO\textsubscript{2}e/m\textsuperscript{3}. Despite considerable advancements that have been made in improving processes performance, the GHG emissions mitigation strategies remains poorly understood and quantified in full-scale wastewater process. Moreover, there is limited research on reducing GHG emission intensity of full-scale wastewater treatment processes, necessitating in-depth research on the strategies to effectively decrease the GHG emission intensity.

In general, several parameters have been identified as factors affecting GHG emissions and intensity in WWTPs, including: treatment process, influent and effluent quality, quantity, energy consumption, and
agent addition, etc. Meanwhile, a low-risk approach for emulating process to reduce GHG emission intensity of wastewater treatment processes is essential, considering more stringent effluent limits. Influent quantity might be an ideal option for optimizing individual processes and reducing GHG intensity in full-scale WWTPs, particularly for A²O + MBR processes, provided that relatively stable effluent quality (Vocks et al. 2005). In this study, we aimed to predict the hyper-quantity functional performance of the typical full-scale A²O + MBR process to guide its operation, and assess GHG emission in practice. The finding of this study can provide valuable insight and a viable technical path to support water and carbon policy-makers in their quest for low-risk and cost-effective solutions for wastewater treatment processes, specifically implication climate change in the future.

2. Methodology

2.1. Scope of this study

The typical A²O + MBR process was implemented at the H-reclaimed WWTP. The WWTP was located in Tongzhou New Town, Beijing, China. The plant covered an area of approximately 2000 hectares, and severed population of around 1.65 million. The facility became functional in November 2013 with a designed treatment capability of $4.0 \times 10^4$ tons per day (Liu et al. 2018). The daily real treated water volume was about 30,000–35,000 t/d, resulting from the membrane flux attenuation before September 2018. In September 2018, the daily water production volume rose to 35,000–40,000 t/d, due to 16 membranes modules upgraded (Liu et al. 2018). At this point the wastewater treatment process was operated with the near full designed capacity. The effluent water quality from WWTP was according to the first-level limit B standard outlined in the local standard ‘Comprehensive Discharge Standard for Water Pollutants’(DB11/307–2013) set by Beijing Municipal. The schematic diagram of the A²O + MBR process is shown in Fig. 1. In this paper, the performance of the process was emulated under eight different conditions to recommend optimal hyper-quantity operations and assess the GHG emissions in the full-scale A²O + MBR process. It was to be regretted that we emulated the performance of the process without electricity consumption mainly due to the complicated control system in the full-scale wastewater treatment system.

2.2 Estimation of the GHG emissions from the WWTP

The GHG emissions considered in this study encompass three main categories (1) direct emissions from the reclaimed WWTPs, which consist of CO₂, CH₄, and NO₂; (2) indirect internal emissions resulting from electricity use during the collection and four wastewater treatment stages, i.e., pre-treatment, biological treatment, disinfection, and sludge treatment; and (3) indirect external emissions originating from the use of chemicals, repair and maintenance of machinery of WWTPs, and administration actives (IPCC. 2021). Meanwhile, according to IPCC, biogenic CO₂ emissions from wastewater are not considered, and thus only CO₂, CH₄ and N₂O emissions from influent and effluent quality of the WWTPs are included in the calculation of GHG emissions in this model. In addition, the emissions from the excess sludge
treatment process are not considered in the paper, although that GHG could been produced during the process.

### 2.3.1. Direct GHG Emissions

The CH$_4$ generation potential of sewage is directly linked to the amount of degradable organics present in the wastewater, which is most commonly measured as 5-day BOD (BOD$_5$). In cases where country-specific data is unavailable, the IPCC recommends using value from a nearby comparable country. The CH$_4$ emissions in this study were calculated using the Tier 1 Methodology as outlined in the 2019 Refinement to the 2006 IPCC guidelines (IPCC. 2021). The direct CO$_2$, N$_2$O, and CH$_4$ emissions and the total GHG emissions from individual WWTP were estimated by using Eq. (1);

\[ EF_i = \sum P_i \times EF_i \times GWP \]

where $P_i$ and $EF_i$ represent the pollutant load (in kg) removal in given year $t$ and emission factors (expressed as GHG emissions per unit of pollutant) associated with each type of GHG emissions, respectively. The $EF_i$ for N$_2$O and CH$_4$ are expressed in the units of kg N$_2$O/kg TN$_{removed}$ and kg CH$_4$/kg BOD$_{removed}$, respectively. Meanwhile, the Global Warming Potential (GWP) values representing the greenhouse effect potential value of different greenhouse gases are considered to be 298, 25, 1, for N$_2$O, CH$_4$ and CO$_2$, respectively (IPCC. 2021).

### 2.3.2. Indirect GHG Emissions

The indirect GHG emissions from each resource can be expressed as follows:

\[ Ce = \sum A_i \times EF_i \times GWP \]

where $Ce$ donates the total GHG emissions generated by the consumption of each resource in WWTP, measured in tCO$_2$e, $A_i$ represents the i-th resource consumption level, and $EF_i$ is the emission factors (EFs) corresponding to the i-th resource (Table 1).
### Table 1
GHG emission coefficient of each resource type

<table>
<thead>
<tr>
<th>Resource types</th>
<th>Carbon emission coefficients unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$</td>
<td>0.086 kgCO$<em>{2e}$/kg BOD$</em>{removed}$</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>0.035 kgCO$<em>{2e}$/kg TN$</em>{removed}$</td>
</tr>
<tr>
<td>Electricity</td>
<td>1.04 kgCO$_{2e}$/kW·h</td>
</tr>
<tr>
<td>Flocculating agents</td>
<td>2.50 kgCO$_{2e}$/kg</td>
</tr>
<tr>
<td>Disinfecting agents</td>
<td>1.40 kgCO$_{2e}$/kg</td>
</tr>
</tbody>
</table>

### 2.3 Test and analysis

The main parameters monitored and tested in this study include: COD, BOD (biochemical oxygen demand), TP (total phosphorus), TN (total nitrogen), NH$_3$-N (ammonia nitrogen), and the quantity of chemical additions. The methodology implemented in this study can be referred to as the 'Water and Wastewater Monitoring and Analysis Method' issued by the Ministry of Environmental Protection of the People's Republic of China (MEP) in 2002 (Ministry of Environmental Protection China (4th edition) 2002). The chemical analytical tests of the samples were performed at the onsite H-reclaimed WWTP laboratory and sent to a third-party lab on a quarterly basis for further analysis. The correlation between chemical additions and operating parameters was examined using Pearson's correlation analysis by SPSS Statistics 26. The overall proposed framework is illustrated in Fig. 2.

Furthermore, the hyper-quantity operation of the A$^2$O + MBR process was predicted by the BioWin software based on ASM2d. The software was provided by the Department of Municipal Engineering, School of Environmental Science and Engineering, Huazhong University of Science and Technology.

### 2.4 Model establishment and its calibration

The model used in this study was established and calibration following the methodology presented in the reported, published by “Desalination and Water Treatment” (Hu et al. 2023). To validate the model, the experimentally measured effluent concentration at different operating conditions was compared with the emulated results obtained from the BioWin software. The average absolute error in between simulated and actual effluent water quality for COD, NH$_3$-N, and TN were determined to be 3.3 mg/L, -0.1 mg/L, and -1.52 mg/L, with corresponding standard deviations (SDs) in simulated values of 2.53, 0.93 and 0.30. However, the total chemical P removal agent used in the model (126 m$^3$) was slightly lower than the actual dosage (150 m$^3$), with an effective mass concentration of Fe not falling below 10%. Despite predictions that the ASM2d model may not be perfect, the results obtained for the simulated effluent can still be acceptable. It can provide a relatively reliable base for the simulating various scenarios in the wastewater treatment processes.
2.5 Scenarios

Eight scenarios (Table 2) were emulated during typical seasons to guide of the WWTP hyper-quantity functional operation for reaching the discharge limits. The addition of carbon sources remained constant across all scenario in order to avoid any effect of the excess sludge treatment capacity. In contrast, varying doses of P removal agents were considered due to effectively removing of TP from the wastewater.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>External carbon source</th>
<th>P removal addition</th>
<th>Emulating quantity</th>
<th>T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>✓</td>
<td>×</td>
<td>1.1Q</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>✓</td>
<td>1.1M</td>
<td>1.1Q</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>✓</td>
<td>×</td>
<td>1.2Q</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>✓</td>
<td>1.2M</td>
<td>1.2Q</td>
<td>14</td>
</tr>
<tr>
<td>5</td>
<td>✓</td>
<td>×</td>
<td>1.3Q</td>
<td>26</td>
</tr>
<tr>
<td>6</td>
<td>✓</td>
<td>1.3M</td>
<td>1.3Q</td>
<td>26</td>
</tr>
<tr>
<td>7</td>
<td>✓</td>
<td>×</td>
<td>1.5Q</td>
<td>26</td>
</tr>
<tr>
<td>8</td>
<td>✓</td>
<td>1.5M</td>
<td>1.5Q</td>
<td>26</td>
</tr>
</tbody>
</table>

Note: Q represents the designed treated water quantity of the H-reclaimed WWTP, and M represents the P chemical removal agents dosing to the A²O + MBR process in the H-reclaimed WWTP (Hu et al. 2023).

3. Result and discussion

3.1 Predicted hyper-quantity functional performance of the process

Considering more stringent effluent limits, it is essential to emulate the performance of the process to recommend optimal hyper-quantity operations. Thus, in this section the performance of the process under eight different conditions in winter and summer is described in Fig. 3.

The average effluent COD concentration in simulated scenarios 1 and 2 (Fig. 3 (a)) were found to be 13.50 mg/L, 13.65 mg/L, 13.45 mg/L and 13.64 mg/L respectively, with corresponding SDs were 2.56, 2.56, 2.59 and 2.58. Notably, the effluent COD concentration under scenarios 1 and 2 showed significant overlap when the water quantity exceeded 1.1 and 1.2 times than that of the design capability during
winter, thereby hardly influencing on effluent COD concentration. In addition, the average effluent concentration of NH$_3$-N in simulated scenarios 1 and 2 (Fig. 3 (b)) were observed to be 0.43mg/L, 0.60 mg/L, 0.34 mg/L and 0.58 mg/L, respectively. Importantly, the NH$_3$-N concentration was found to achieve the discharge limit even under 1.2 times the hyper-quantity (4.8×10$^4$ t/d). Conversely, the emulated effluent quality in scenarios 2 and 4 following the addition of P removal agents (mainly Fe ions) showed higher fluctuations. The effluent TP concentration was noticeably higher compared to scenarios without the dosing phosphorus removal agent, indicating the negative effect of P removal agent on the NH$_3$-N effluent concentration (Fig. 3 (b)). Furthermore, the average effluent TN concentration in simulated process were observed to be 11.20mg/L, 11.34 mg/L, 11.76 mg/L and 11.94 mg/L, respectively. The TN concentration remained below the limit of 15 mg/L for effluent concentration, when the influent quality was increased to 1.1 and 1.2 times the design scale. However, the risk of exceeding the discharge limits existed to a certain extent. Therefore, there was still a certain level of risk of exceeding the discharge limits, and special attention should be given to the effluent concentration of NH$_3$-N and TN during hyper-quantity operation in winter (Fig. 3 (c)). The average simulated effluent TP concentration were observed to be 0.41 mg/L, 0.0066 mg/L, 0.75 mg/L and 0.0065 mg/L, respectively. It is worth noting that the effluent TP concentration without any TP removal agents dosing exceeded the discharge standard by a margin. When the P removal agents were added, the effluent TP concentration showed an expectingly reached discharge standard (Fig. 3 (d)). In summary, 1.2 times the influent quantity is recommended, and the effluent NH$_3$ and TN concentration should be given to special attention in winter.

Under emulating conditions 5 to 8 (Fig. 3 (e)), the average effluent COD concentration was measured to be 14.03 mg/L, 13.80 mg/L, 13.94 mg/L and 13.79 mg/L, respectively. It was observed that the effluent COD concentration remained relatively unchanged when the water quantity exceeded 1.3 times and 1.5 times effluent quality during summer. However, the average emulating effluent COD concentration were slightly higher compared to emulating conditions 1 to 4. The average NH$_3$-N effluent concentration for 5 ~ 8 scenarios (Fig. 3 (f)) was found to be 0.43mg/L, 0.60 mg/L, 0.34 mg/L and 0.58 mg/L, respectively. It can be seen that the NH$_3$-N concentration easily achieved the discharge limit even during 1.3 and 1.5 times of hyper-quantity operation in summer. Nevertheless, the simulated effluent TN concentration under scenarios 6 and 8 following the addition of P removal agents (mainly Fe ions) exhibited relatively higher fluctuations. The average effluent TN concentration under these simulating conditions was measured to be 11.20mg/L, 11.34 mg/L, 11.76 mg/L and 11.94 mg/L, respectively. The effluent TN concentration remained below the discharge limit of 15 mg/L effluent concentration, when the influent water quantity was increased to 1.3 and 1.5 times (Fig. 3 (f)). However, that effluent TN concentration frequently exceeded the discharge limits, especially when 1.5 times the dosage of the P removal agent was added. Thus, 1.3 times the influent quantity is recommended to operate, and special attention should be given to the effluent COD and TN concentration during hyper-quantity operation in summer. Additionally, the average effluent concentration of TP in the emulated water were found to be 0.41 mg/L, 0.0066 mg/L, 0.75 mg/L and 0.0065 mg/L, respectively, for scenarios 5 to 8. It is noticed that the effluent TP concentration was significantly higher when P removal agent was added compared to the scenarios.
without their addition, indicating the negative effect of these agents on effluent NH$_3$-N concentration (Fig. 3 (g)) (Jia et al. 2016). Meanwhile, the concentration of effluent TP exceeded the standard considerably, when the P removal agent was not enhanced at the same multiple as the treated quantity. In contrast, the effluent quality reached the standard completely, as the dosing of P removal agents was increased (Fig. 3 (g)).

### 3.2 Performance of the process

The daily average treated quantity in 2022 reached around $5.1 \times 10^4$ t/d, demonstrating a 50% increase (Fig. 4 (a)) compared to the 2018 level of $3.4 \times 10^4$ t/d. The average treated quantity in January, February and December was nearly $4.88 \times 10^4$ t/d, which was close to the emulated typical winter scenarios $4.8 \times 10^4$ t/d. Furthermore, the average treated quantity in May, June and July was $5.27 \times 10^4$ t/d, which was 1.3 times the designed water quantity of the typical summer project set to $5.2 \times 10^4$ t/d.

Table 3 presented the statistical data regarding the performance of the A$^2$O + MBR process during the hyper-quantity operational periods.

<table>
<thead>
<tr>
<th>Statistics data of the A$^2$O + MBR process performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>Average concentration$_{influent}$ (mg/L)</td>
</tr>
<tr>
<td>Average concentration$_{effluent}$ (mg/L)</td>
</tr>
<tr>
<td>Discharge limits (mg/L)</td>
</tr>
<tr>
<td>Average removal efficiency (%)</td>
</tr>
</tbody>
</table>

**Table 4**

Correlation of the main influent water quality

<table>
<thead>
<tr>
<th>BOD</th>
<th>COD</th>
<th>NH$_3$-N</th>
<th>TN</th>
<th>TP</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD</td>
<td>1</td>
<td>0.999**</td>
<td>0.314</td>
<td>0.303</td>
</tr>
<tr>
<td>COD</td>
<td>1</td>
<td>0.306</td>
<td>0.294</td>
<td>0.502</td>
</tr>
<tr>
<td>NH$_3$-N</td>
<td>1</td>
<td>0.997**</td>
<td>0.029</td>
<td></td>
</tr>
<tr>
<td>TN</td>
<td>1</td>
<td>0.041</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5
SDs of monthly average concentration for effluent water quality (mg/L)

<table>
<thead>
<tr>
<th>Years</th>
<th>BOD</th>
<th>COD</th>
<th>NH₃-N</th>
<th>TN</th>
<th>TP</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>24.03</td>
<td>45.75</td>
<td>5.21</td>
<td>5.36</td>
<td>0.30</td>
</tr>
<tr>
<td>2022</td>
<td>16.31</td>
<td>33.10</td>
<td>2.14</td>
<td>2.21</td>
<td>0.30</td>
</tr>
</tbody>
</table>

The influent concentrations of BOD and COD exhibited a similar trend in 2022, gradually decreasing from the first half of the year to the second half of the year. On the other hand, the influent concentration of NH₃-N, TN and TP remained relatively stable throughout the year. The main discharge limits were consistently reached during this period. The A²/O + MBR process proved to be effective during the hyper-quantity operational periods. The real treated water quantity is closely aligned with emulating predictions, indicating the reliability of the ASM model played a particularly important role in predicting the quantity and quality.

### 3.3 Impact on the GHG emission

#### 3.3.1 Variations in total GHG emission and intensity

The total GHG emissions form the WWTP was 23.33 ktCO₂e in 2022, which represented a 42.69% increase, compared to the 2018 level (16.35 ktCO₂e). This increase can be attributed to the higher treated quantity of the WWTP. The GHG emissions and intensity showed minor fluctuation over the analyzed period (Fig. 5 (b)). The monthly total GHG emissions were projected to be relatively constant throughout the year (1.9 ktCO₂e), except in May. The lowest monthly emissions of 1.60 ktCO₂e were observed in August, while the highest emissions of 2.21 ktCO₂e occurred in December (Fig. 5 (a)). Furthermore, the annual GHG emissions from CH₄, N₂O, electricity consumption and chemical agent consumption GHG emissions were 4.75 ktCO₂e, 7.44 ktCO₂e, 11.12 ktCO₂e, 13.11 ktCO₂e, respectively (Fig. 5 (b)). In terms of the overall contribution of GHG emissions, CH₄ accounted for 20.38%, N₂O accounted for 31.89%, electricity accounted for 47.67% and chemical agent consumption accounted for 0.06%, as illustrated in Fig. 6.

The total GHG emission intensity, measured in kg CO₂e/m³ of wastewater) was 1.24 kgCO₂e/m³ (Fig. 5 (b)) in 2022. This represented a decreased of 5.3% compared to the 2018 level. Moreover, the average GHG emission intensity for CH₄, N₂O, energy consumption and material consumption were found to be 0.25 kgCO₂e/m³, 0.39 kgCO₂e/m³, 0.59 kgCO₂e/m³ and 0.00070 kgCO₂e/m³, respectively (Fig. 5 (b)), with their increase of 7.4%, 7.1%, 4.9%, 12.5%, respectively.

Further, among the total GHG emissions, CH₄, N₂O, consumption of electricity and chemical agents accounted for 20.38%, 31.89%, 47.67% and 0.06% of the total GHG emissions (Fig. 6), respectively, suggesting that electricity consumption remained the largest contributor to the total GHG emissions. In
comparison, the respective proportions in 2018 were 20.91%, 32.19%, 48.84%, and 32.19% (Hu et al. 2021). The proportion of the four types of GHG emissions nearly unaltered during the hyper-quantity operational period, showing minimal changes compared to those in 2018. However, the total GHG emissions increased as the treated quantity of wastewater increased. Notably, there were a 1.17% reduction in proportion of energy-related GHG emissions, ascribing to the improvement of the aeration efficiency within the activated sludge system. In general, achieving carbon mitigation target often requires carbon- and energy-intensive industries to reduce production, resulting in economic loss for these industries. Nevertheless, moderate hyper-quantity operation can offer dual benefits. It not only helps to reduce GHG emission intensity to some extent but also provides advantages for the operating sectors.

### 3.3.2 Variations in the direct and indirect GHG Emission

Characteristics of the indirect and direct GHG emissions are shown in Fig. 7. The highest monthly emissions of CH$_4$ and N$_2$O emissions were recorded in January (470.41 tCO$_2$e) and April (685.75 tCO$_2$e), while the lowest emissions were observed in May (376.23 tCO$_2$e) and December (556.75 tCO$_2$e), respectively (Fig. 7 (a)). The average monthly direct CH$_4$ and N$_2$O emissions were estimated at 396.41 tCO$_2$e and 620.16 tCO$_2$e, showing an increase of 28.11% and 41.41%, respectively, compared to the levels recorded in 2018.

Besides, the highest monthly indirect emissions from electricity consumption and chemical consumption emissions were observed in January. (1070.81 tCO$_2$e) and November (1.21 tCO$_2$e) (Fig. 7 (b)), whereas the lowest values occurred in May (575.28 tCO$_2$e) and February (0.88 tCO$_2$e), respectively (Fig. 7 (b)). The average monthly indirect GHG emissions for energy consumption and chemical consumption were found to be 927.22 tCO$_2$e and 1.09 tCO$_2$e, respectively (Fig. 7 (b)), demonstrating an increment of 45.3% and 29.76%, respectively, compared to the levels in 2018. Overall, the growth rate of carbon emissions from N$_2$O and energy consumption were consistent with the growth rate of treated water (50%).

### 3.4 Sensitivity analysis for GHG emission intensity at different quantities

The sensitivity analysis conducted using the running data from the H-reclaimed WWTP in 2018 and 2022 revealed interesting findings. There was a weakly linear trend observed in the total GHG emission as the percentage change in treated water inclined increase until the quantity achieved the designed treated capacity (Fig. 8 (a)). Further, the percentage change for the GHG emissions varied from −20–20% at the lower treated quantities (Fig. 8 (a)). However, when the process operated at hyper-quantity conditions, exceeding the design capability 22.5–37.5%, the percentage change in the GHG emissions intensity (-12.5–12.5%) showed higher fluctuation than the total GHG emissions (35–55%) (Fig. 8 (b)). Similar trends were observed in the types of GHG emissions (Fig. 8 (c, d and e)). Additionally, weakly negative correlations were manifested between influent wastewater quantity and different types of GHG...
emissions (Hu et al. 2021). This trend also supported by sensitivity analysis, illustrating a similar of pattern in the intensity of different types of GHG emissions, except for the N₂O emission intensity.

The sensitivity analysis suggested that increasing the percentage change in the treated quantity of WWTP does not always result in an equivalent percentage decrease in GHG emissions intensity. The marginal benefit of this measure appeared to diminish, particularly, when the treated quantity exceeded approximately 125% of the design capability. Moreover, the ASM emulating results also displayed that when the treated quantity exceeds the nearly 125% of the design capability, the risk of effluent quality exceeding the discharge limits increased dramatically especially during winter. Thus, it becomes imperative to explore other technologies and strategies to reduce the GHG emission intensity. In this regard, Su et al. (Su et al. 2023) revealed a potential 29% reduction in GHG emission and intensity by implementing a 0 to 10% reduction in GHG emission in imported electricity. However, it should be noted that the sensitivities of GHG emissions, GHG emission intensity, and water quality to other engineering technologies were ignored in this paper, highlighting the need for a more accurate model and cross-agency collaboration to implementation for future implementation.

4. Conclusion

Our research demonstrated a low-risk approach to decrease the GHG emission intensity in wastewater treatment processes for operating sectors. The performance of the process was emulated under eight different conditions to recommend optimal hyper-quantity operations, considering more stringent effluent limits. The real operation of the process suggests that hyper-quantity operation leads to a decrease in GHG emission intensity. The sensitivity analysis illustrates that an increasing percentage change of the treated quantity in the WWTP does not necessarily result in a corresponding in the percentage change of GHG emissions intensity during the hyper-quantity operational period. Meanwhile, the marginal benefit of the hyper-quantity operation appeared to decline, particularly when the average treated quantity exceeded approximately 125% of the design capability. Given that hyper-quantity operation led to a decrease in the GHG emission intensity, it could be concluded that moderate hyper-quantity operation is accepted.

Declarations

Author contribution

Yongfeng Hu: data collection, writing-reviewing and editing, methodology, and software. Yongxiang Zhang: data curation and methodology supervision. Ruirui Sun: picture drawing. Kun Wang: data curation and methodology. Qing Cai: supervision. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit it for publication. All the authors contributed to the design of the study and the final manuscript.

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Data availability

All data generated or analyzed during this study are included in this published article.

Declaration of interest

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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**Figures**

![Figure 1](image.png)

Figure 1

Schematic diagram of the $A^2/O+MBR$ process
Figure 2

Proposed framework overview
Figure 3

Performance of the process at emulating conditions in winter and summer

Note: The influent concentrations (experiment) are shown on the left axis, and other indicators are on the right axis.
Figure 4

Monthly average treated quantity (a) and real performance of the process (b, c, and d)
Figure 5

Characteristics of the total GHG emissions (a) and intensity (b)

Figure 6

Proportion of four types of the GHG emissions
Figure 7

Characteristics of the direct and indirect GHG emissions
Figure 8

Sensitivity analysis for the GHG emissions (a), GHG emission intensity and, N₂O, CH₄ and electricity GHG emission intensity (b, c, d and e)