

High-spatiotemporal-resolution mapping of non-carbon dioxide emission hotspots from China's wastewater treatment plants

Huiwen Yang, Yue Zhu, Xu Zhao(✉)

Institute of Blue and Green Development, Shandong University, Weihai 264209, China

Abstract

Emissions of non-carbon dioxide greenhouse gases (non-CO₂ GHGs), primarily methane (CH₄) and nitrous oxide (N₂O), are critical drivers of climate change, with China's wastewater treatment sector ranking as the fourth-largest source of both gases. Consequently, establishing high-spatiotemporal-resolution inventories for CH₄ and N₂O emissions from this sector is a prerequisite for China to achieve its non-CO₂ GHG mitigation targets. This study develops a 0.1° × 0.1° spatial-resolution inventory for CH₄ and N₂O emissions from Chinese wastewater treatment plants (WWTPs) spanning 2000–2024. By integrating top-down and bottom-up methodologies, the inventory is used to establish a refined emission-factor database that distinguishes between technical processes and wastewater types. The results indicate that non-CO₂ GHG emissions of China's WWTPs generally increased until 2015, followed by a steady decline through 2024. Emission hotspots have expanded from eastern to central China, with the top 10% of WWTPs accounting for around 60% of total emissions. These datasets provide a scientific basis for designing region-specific emission-mitigation policies.

Keywords

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1 Introduction

Non-carbon dioxide greenhouse gases (non-CO₂ GHGs), mainly methane (CH₄) and nitrous oxide (N₂O), are major contributors to climate change, with their global warming potentials being 27 and 273 times that of CO₂, respectively [1]. As the world's largest emitter of non-CO₂ GHGs, China's mitigation efforts will exert far-reaching effects on a global scale [2]. China's 2024 emission statistics from the Emission Database for Global Atmospheric Research revealed that the wastewater treatment sector is a major contributor, ranking as the fourth-largest source of CH₄ and N₂O emissions among 31 and 29 sectors, respectively [3]. Consequently, wastewater treatment has become a key priority area for industrial decarbonization, following energy, transportation, and buildings, and emerging as a crucial lever for advancing synergistic pollution and carbon-emission mitigation. In this context, quantifying non-CO₂ emissions from this sector is a prerequi-

site for achieving the nation's mitigation targets. However, CH₄ and N₂O generation and release during wastewater treatment are highly influenced by operational conditions, such as dissolved oxygen, temperature, and chemical oxygen demand (COD) [4,5], while emission profiles vary significantly across different treatment processes [6]. This variability greatly complicates accurate emission quantification, posing substantial challenges for establishing high-resolution emission inventories.

Despite extensive studies using emission-factor (EF) methods [2,7], field monitoring [8], or model simulations [9,10], existing CH₄ and N₂O inventories from Chinese wastewater treatment plants (WWTPs) still suffer from incomplete time series coverage and poor data consistency. Existing time series-level studies on CH₄ and N₂O emissions from WWTPs mainly explored single years [2,11] or lack data on the latest discharge status [12,13]. Notably, the inherent limitations of standard calculation methods introduce high result uncertain-

✉ Address correspondence to Xu Zhao, xuzhao@sdu.edu.cn

ties. The traditional top-down approach relies on national or provincial macrolevel data, which complicate the capture of individual emission variations across WWTPs. While the bottom-up approach utilizes actual measurement data, it is constrained by sample representativeness and data gaps, which often result in the underestimation of regional total emissions. This discrepancy complicates the comparability of existing regional or national studies on CH₄ and N₂O emissions from WWTPs. For instance, Zhao et al. [14] calculated CH₄ emissions using plant-level activity data and the 2006 Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories (IPCC 2006) EFs [15], whereas Yan et al. [16] derived EFs by averaging values from multiple studies, followed by estimating CH₄ emissions using provincial-level activity data. Such EF and data-source discrepancies have led to a 38-fold variance in calculated CH₄ emissions for the same year [17]. Furthermore, Song et al. [18] demonstrated that GHG emissions from the same WWTP can span 4–6 orders of magnitude, driven by highly variable factors, such as operational conditions, seasons, and temperature.

To address these challenges and maximize the accuracy of emission accounting, this study employed an integrated top-down and bottom-up methodology to construct a high-spatial-resolution (0.1° × 0.1°) CH₄ and N₂O emission inventory for Chinese WWTPs spanning 2000–2024. Employing provincial macrolevel data, the removed amounts of COD and total nitrogen (TN) for each province and municipality from 2000 to 2024 were calculated, ensuring total emission estimates align with official national and regional environmental statistics. Conversely, the bottom-up approach details the microlevel aspects. We collected plant-level operational data from 4550 WWTPs to establish a refined EF database that distinguishes among wastewater types and treatment technologies. This integrated approach retains detailed microlevel data while significantly mitigating deviations typically caused by incomplete microlevel data.

2 Methodology and data

2.1 Emission-inventory compilation

During emission accounting and inventory compilation, EFs vary significantly among wastewater treatment technologies [19–21]. Therefore, this study classifies these technologies into two main categories based on their core treatment mechanism: aerobic and anaerobic processes. Second, WWTP influents comprise domestic and industrial wastewater, which require distinct treatment processes and generate different emission levels. Consequently, this study distinguishes between these two source categories. Third, an EF database tailored to China's national conditions was established based on the default values from the IPCC 2019 Guidelines and

benchmarks from relevant literature. Finally, direct CH₄ and N₂O emissions from wastewater treatment were estimated by integrating plant- and provincial-level activity data.

Classification of wastewater treatment processes. To improve emission-estimation accuracy, the specific treatment technologies adopted by each WWTP must be identified and categorized. Depending on different actual treatment requirements, Chinese WWTPs may adopt primary, secondary, or tertiary treatment processes, each encompassing multiple distinct technological configurations. Because technology-level data could not be collected for each WWTP, this study relied solely on plant-level data (i.e., the operational data of an entire WWTP). To simplify the estimation of CH₄ and N₂O emissions from various WWTPs, it was necessary to first determine the main categories of wastewater treatment technologies, followed by classifying them as aerobic and anaerobic processes. Finally, the corresponding EFs were selected for emission accounting. Table 1 lists the main technological categories and their classification into aerobic and anaerobic processes.

Emission-factor database. Besides treating domestic wastewater, WWTPs also treat industrial wastewater under certain conditions. In this case, the IPCC 2019 Guidelines recommend consolidating cotreated domestic and industrial streams under a unified domestic framework [22]. However, the two

Table 1 Classification of wastewater treatment technologies and processes.

Core technology	Classification
Anaerobic/aerobic (A/O)	Anaerobic
Anaerobic/anoxic/aerobic process (A2/O)	Anaerobic
Adsorption-biodegradation (AB)	Aerobic
BIOLAK	Aerobic
Sequencing batch reactor (SBR)	Anaerobic
V-type filter (VT)	Aerobic
Integrated traditional process and oxidation ditch	Aerobic or anaerobic
Conventional activated sludge (CAS)	Aerobic
Chemical treatment	Aerobic
Chemically enhanced primary treatment	Aerobic
Biological filter	Aerobic
Land treatment	Aerobic
Physical treatment	Anaerobic
Physicochemical treatment	Aerobic
Oxidation ditch (OD)	Aerobic
Oxidation pond (OP)	Aerobic or anaerobic
Constructed wetland	Aerobic or anaerobic

wastewater types differ in influent quality and treatment requirements. To improve accounting accuracy, this study distinguishes between domestic and industrial wastewater, providing different EFs. Among these, the CH₄ EF for industrial wastewater (EF₁) represents a generalized national estimate [23]. The CH₄ EFs for aerobic and anaerobic (EF₂ and EF₃, respectively) domestic wastewater treatment processes adopt the default values from the IPCC 2019 Guidelines, whereas the N₂O EF (EF₄) represents a generalized national estimate [24]. The flowchart for establishing the EF database is shown in Fig. 1.

Calculation of methane and nitrous oxide emissions.

During wastewater treatment, CH₄ and N₂O constitute major GHG components. Their direct emissions from WWTPs are calculated using Eqs. 1 and 2, respectively.

$$\text{CH}_4_{\text{emissions}} = \text{EF}_i \times \text{COD}_{\text{removed}} \quad (1)$$

$$\text{N}_2\text{O}_{\text{emissions}} = \text{EF}_i \times \text{TN}_{\text{removed}} \times 44/28 \quad (2)$$

where CH₄_{emissions} and N₂O_{emissions} represent the CH₄ and N₂O emissions during WWTP activity, EF_{*i*} (kg CH₄/kg COD_{removed} or kg N₂O/kg TN_{removed}) is the *i*-th EF in the library, COD_{removed} is the removed amount of COD during wastewater treatment, and TN_{removed} is the removed amount of total nitrogen.

Compilation of high-spatiotemporal-resolution emission inventory. Based on the integrated top-down and bottom-up methodologies, this study integrates multisource data to construct a high-spatiotemporal-resolution non-CO₂ GHG emission inventory for Chinese WWTPs.

Specifically, provincial-level COD_{removed} and TN_{removed} values spanning 2000–2024 were derived from the China Environmental Statistics Yearbook and subsequently revised based on actual plant-level data to improve long-term data reliability. The revision was executed as follows: for the 2014–2018 period, that is, the timeframe covered by the Urban Drainage Statistical Yearbook [25], the pollutant-removal data for the 4550 WWTPs within each province were aggregated to determine the “plant-level aggregated total.” The revision coefficient (RC_{prov}) for each province was defined as RC_{prov} = plant-

level aggregated total/provincial initial value. The provincial initial value is calculated based on the China Environmental Statistical Yearbook [26]. There were no complete plant-level data for years outside this 2014–2018 window. Thus, we use the average RC_{prov} (RC_{prov-average}) of this timeframe to revise the corresponding provincial initial value (provincial initial value × RC_{prov-average}) to ensure consistency between the long-term and observed provincial and plant-level data, respectively.

Second, leveraging the unique allocation coefficient (AC) of each facility, the revised provincial-level pollutant-removal data were downscaled and assigned to individual WWTPs on an annual basis to construct a long-term time series plant-level temporal dataset. From 2014 to 2018, the AC of the *i*-th WWTP within a given province in a certain year (AC_{*i*,prov,year}) was defined as the ratio of the WWTP's capacity to the total treatment capacity of provincial WWTPs in that year (AC_{*i*,prov,year} = Q_{*i*,prov,year}/ΣQ_{*j*,prov,year}, where *j* = 1 to *n*). Here, *n* is the total number of provincial WWTPs in that year, and *Q* represents the treatment capacity of a WWTP. The adjusted plant-level COD_{removed} is thus: plant-level COD_{removed} = Revised provincial COD_{removed} × AC_{*i*,prov,year}, and the adjusted plant-level TN removal amount is calculated similarly. In other years, the AC of each plant adopts the average AC of that plant from 2014 to 2018, while other conditions are kept the same.

Consequently, by combining these datasets with plant-level EFs, we calculated the CH₄ and N₂O emissions from each WWTP from 2000 to 2024. Finally, the WWTP non-CO₂ GHG emissions were allocated to a grid scale with a spatial resolution of 0.1° × 0.1°, thereby constructing a nationwide, high-spatiotemporal-resolution non-CO₂ GHG emission inventory. Actual GPS coordinates (latitude and longitude) for each WWTP were collected from the national environmental monitoring platform, official registration records, and provincial ecological bulletins. Emissions from each WWTP were directly assigned to the 0.1° × 0.1° grid cell containing its coordinates, with emissions from multiple WWTPs in the same grid aggregated. This direct spatial assignment eliminates the uncertainty of centroid-based aggregation and ensures high spatial accuracy.

2.2 Data

Plant-level data. The original data of the COD_{removed} volume, TN_{removed} volume, treatment technology type, and treatment scale were obtained from the Urban Drainage Statistical Yearbook (Society of Chinese Urban Water Supply and Drainage, 2015–2019) [25]. This book provides comprehensive operational metrics for 4550 WWTPs across China.

Provincial-level data. The original data of the COD_{removed} and TN_{removed} volumes, etc., in other years were obtained from the China Environmental Statistical Yearbook [26], which

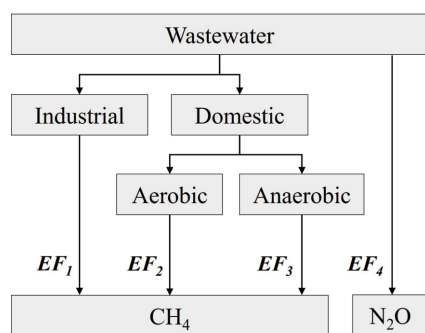


Figure 1 Emission factors for CH₄ and N₂O.

provides wastewater-related indicators for all 31 Chinese provinces; these metrics were used to calculate provincial $\text{COD}_{\text{removal}}$ and $\text{TN}_{\text{removal}}$.

Geolocation data of the wastewater treatment plants. The geographic information of each WWTP was obtained by searching the official registered business address of the facilities. The business addresses were geocoded into geographic coordinates (latitude and longitude), after which the coordinate accuracy was verified by cross-referencing with local ecological environment bureau public notices.

Emission-factor data. The EF database was developed based on the IPCC 2019 Guidelines and related literature [23–30]. The IPCC 2019 Guidelines provide default values for various WWTP EFs [22]. Additionally, under the constraints of China's specific national conditions, applicable and reasonable domestic EFs were incorporated into the EF database [23–30].

3 Results

3.1 Trend and characteristics of non-carbon dioxide greenhouse gas emissions

Temporal trend of non-carbon dioxide greenhouse gas emissions. From 2000 to 2024, China's WWTP non- CO_2 GHG emissions exhibited an initially increasing trend before stabilizing. Among these, emissions from domestic wastewater dominated, whereas contributions from industrial wastewater decreased significantly in the later period. Regarding the emission structure, domestic wastewater served as the main source of CH_4 emissions, with its emissions increasing from approximately 239 Gg in 2000 to a maximum value of approximately 2475 Gg in 2015 before stabilizing at approximately 2000 Gg. CH_4 emissions from industrial wastewater treatment reached a peak value in 2009 before gradually decreasing, becoming only approximately 98 Gg in 2024 (Fig. 2). This reflects the strengthened efforts in industrial wastewater treatment over time. N_2O emissions from domestic wastewater also increased gradually as the volume of domestic wastewater increased. Conversely, N_2O emissions

from industrial wastewater remained at a low level, only fluctuating slightly. Thus, domestic wastewater was the main driver of non- CO_2 GHG emissions, with its growth heavily related to the increase in domestic wastewater generation during rapid urbanization. Conversely, the late-stage decline in industrial wastewater emissions was related to the transformation of industrial structure, the improvement of pretreatment capabilities, and the implementation of pollution-mitigation policies.

Overall spatial distribution and evolution. The spatial characteristics of Chinese WWTP non- CO_2 GHG emissions spanning 2000–2024 were characterized by a significant expansion of high-emission areas and growth inertia in some regions (Fig. S1 in Electronic Supplementary Materials (ESM)). In 2000, CH_4 and N_2O emissions were only concentrated in eastern China, such as the Shandong Peninsula and Yangtze River Delta, with a few provincial capitals exhibiting point-like high values. However, by 2024, the high-emission areas had covered most provinces in northern, eastern, and central China, with emission hotspots increasing significantly in central and western provinces, such as Guizhou and Inner Mongolia. However, non- CO_2 GHG emissions in the Qinghai–Tibet Plateau remained low. These spatial distribution patterns were caused by uneven expansion of regional WWTP layouts driven by rapid urbanization. Due to its large baseline wastewater treatment volume, eastern China consistently maintained high emissions. The accelerated construction of WWTPs in central and western China has significantly enhanced wastewater treatment, rapidly increasing emissions. Remote areas, represented by the Qinghai–Tibet Plateau, were still characterized by low emissions owing to the low coverage rate of WWTPs there.

Identification of local emission hotspots. In 2000, CH_4 emission hotspots from WWTPs were concentrated within Shandong and Zhejiang (Fig. S1 in ESM). Specifically, facilities in Shandong emitted a total of 80.10 Gg of CH_4 , accounting for 18.8% of the national aggregate. The N_2O emission hotspots were mainly in Jiangsu and Sichuan, with the N_2O emissions from Jiangsu facilities accounting for 11.7% of

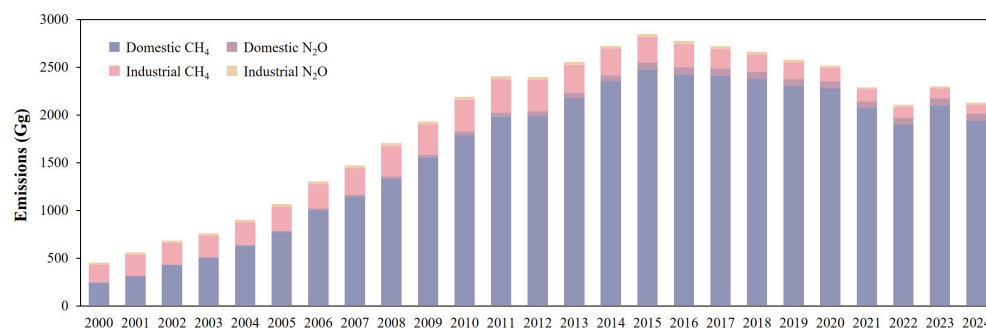


Figure 2 Emissions of non-carbon dioxide greenhouse gases (non- CO_2 GHGs) from Chinese wastewater treatment plants (WWTPs) from 2000 to 2024.

the national aggregate. By 2024, new CH₄ emission hotspots had expanded to Hebei and Guangdong, making the combined CH₄ emissions in these two provinces account for 20% of the national aggregate. However, N₂O emission hotspots remained concentrated in the eastern coastal areas, with the total emissions in Guangdong, Jiangsu, and Shandong accounting for 24.3% of the national aggregate. Additionally, the CH₄ emission growth rate in central and western China, such as Shaanxi and Henan, exceeded eight times the original values, making them emerging CH₄ emission hotspots. Concurrently, N₂O emissions in north China increased significantly, making the region an emerging N₂O emission hotspot. By comparison, the diffusion of high-CH₄-emission areas was more rapid and extensive.

Prominent contributions of super-emission sources. The Lorenz curves for CH₄ and N₂O emissions were constructed to identify emission concentrations (Fig. 3). The curves exhibit a steep tail feature, indicating a highly uneven emission distribution. Additionally, a few WWTPs account for the highest CH₄ and N₂O emissions. In 2000 and 2024, the top 10% of WWTPs contributed 65.0% (60.0%) and 60.3% (53.3%) of national CH₄ (N₂O) emissions, respectively. These WWTPs are super-emission sources that dominate non-CO₂ GHG emissions. The emission scale of such super-emitting WWTPs can often directly determine the emission level of their respective regions. Therefore, prioritizing the governance of these point sources is a highly efficient strategy for mitigating the GHG emissions from the sector, enabling significant emission reduction within a minimized regulatory scope. Taking 2024 as an example, Guangdong ranked first nationwide in N₂O emissions; its top 10% of super-emitting WWTPs were highly concentrated within the Pearl River Delta Economic Zone, contributing 49.7% of the provincial aggregate (Fig. S1 in ESM). This geographic agglomeration facilitates centralized governance. Targeted strategies, such as the unified upgrading of treatment processes and the implementation of centralized

operation and maintenance protocols, can be deployed to simultaneously curtail the emission levels of multiple super-emitter sources through regionalized governance measures. Consequently, this coordinated approach reduces governance costs while rapidly reducing regional emission aggregates.

3.2 Influencing factors of non-carbon dioxide greenhouse gas emissions from Chinese wastewater treatment plants

Having identified the non-CO₂ GHG emission profiles of Chinese WWTPs, this study further evaluates the inherent attributes of these facilities to isolate core influencing factors, followed by in-depth analysis. Compared with exogenous, uncontrollable factors, such as the economy and population, wastewater treatment technology and facility scales, as internal controllable operation and construction parameters, demonstrate higher practicality for targeted emission-reduction optimization. Therefore, leveraging the 2018 WWTP operational data, wastewater treatment technologies were categorized into six processes: A/O, A₂/O, SBR, OD, CAS, and other. With reference to specifications, such as the Discharge standard of pollutants for municipal wastewater treatment plants [30], WWTPs were divided into four categories (small-, medium-, large-, and extra-large-scale categories) based on their daily treatment capacities, covering wastewater treatment scenarios across different levels. The specific classification standards are summarized in Table 2.

Impact of differences in wastewater treatment scales on emissions. Wastewater treatment scale exhibits positive correlations with CH₄ and N₂O emission intensities, although CH₄ emission intensity increases more rapidly (Fig. 4). Across small-scale to extra-large-scale WWTPs, its intensity gradually increases from 29.00 g/m³ to 45.83 g/m³, with the emission intensity from extra-large-scale WWTPs being 1.59 times that of small-scale facilities. This may be because extra-large-scale WWTPs handle large volumes of wastewater, resulting in

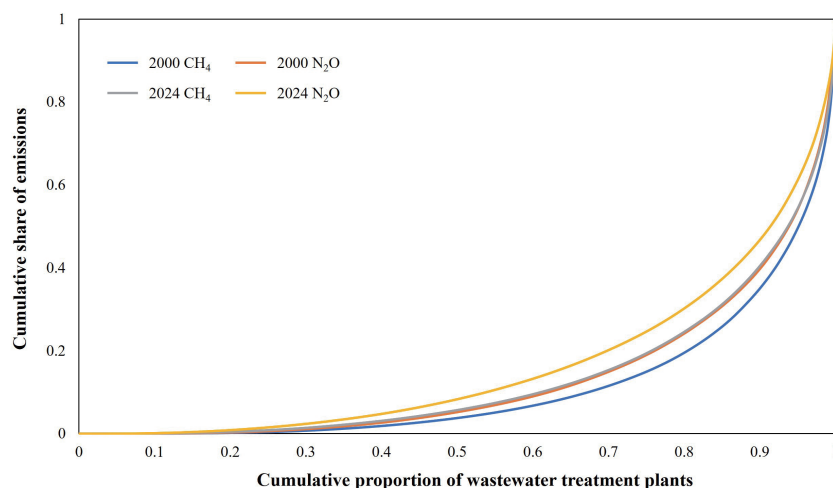


Figure 3 Lorenz curves of CH₄ and N₂O emissions from WWTPs from 2000 to 2024.

Table 2 Classification criteria for wastewater treatment capacity.

Scale type	Standard	Description
Small	$<5 \times 10^4 \text{ m}^3/\text{d}$	County- and township-level WWTPs
Medium	$(5-10) \times 10^4 \text{ m}^3/\text{d}$	WWTPs affiliated with urban areas and industrial parks
Large	$(10-50) \times 10^4 \text{ m}^3/\text{d}$	Urban main WWTP
Extra large	$>50 \times 10^4 \text{ m}^3/\text{d}$	Megacity core WWTP

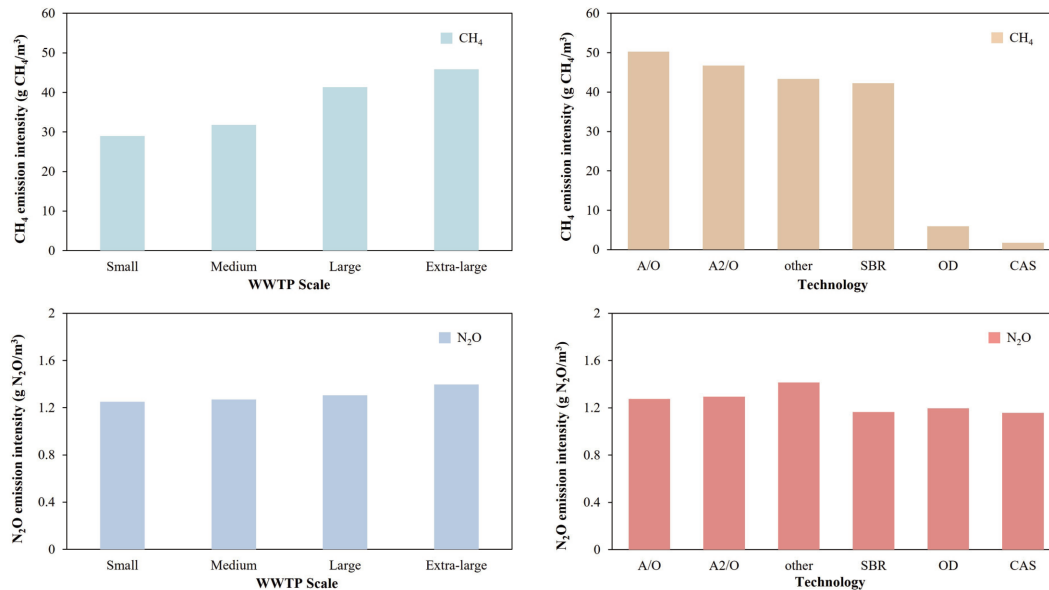


Figure 4 Emission intensities of CH₄ and N₂O from WWTPs across different technologies and scales.

higher operational loads in their A2 units, which are more prone to CH₄ accumulation. Concurrently, large-scale WWTPs mostly adopt processes, such as A/O and A2/O, that simultaneously achieve organic matter degradation, as well as nitrogen and phosphorus removal, further increasing the emission intensity. Conversely, the N₂O emission intensity slightly increased from 1.25 g/m³ (small-scale) to 1.40 g/m³ (extra-large-scale) with the increasing scale, representing an approximately 12% growth. This indicates that the nitrogen-removal processes in larger WWTPs operate more frequently, yielding slightly higher N₂O byproducts, although the overall fluctuation was much smaller than that of CH₄.

Impact of the differences in wastewater treatment technology on emissions. Differences in process technologies exert a highly significant impact on CH₄ emission intensity while barely affecting N₂O emission intensity (Fig. 4). Specifically, the CH₄ emission intensities of processes, including A/O, A2/O, and SBR, are as high as 42.28–50.24 g/m³, whereas those of OD and CAS are only 1.78–5.90 g/m³, representing a more than sevenfold disparity. This is because the A2 zones in the A/O and A2/O processes are more likely to create methanogenic environments, whereas the OD and CAS processes exhibit more sufficient aeration that inhibits CH₄ pro-

duction and diffusion. Conversely, the N₂O emission intensity exhibits relative stability across various process technologies, remaining the same at 1.16–1.42 g/m³, with only negligible fluctuations. This indicates that N₂O production is more related to the nitrogen concentration in sewage rather than the deployed treatment process.

Differentiated measures necessary for emission reduction. CH₄ emissions are more significantly affected by process-technology type and WWTP scale. Consequently, mitigation strategies must prioritize the promotion of low-CH₄-emitting processes, such as OD and CAS, or the optimization of the aeration and anaerobic-zone operating parameters within existing A/O and A2/O systems while avoiding the blind expansion of WWTPs. Conversely, because N₂O emissions are less sensitive to process configuration and plant scale, mitigation efforts must target source control of influent nitrogen or the optimization of links, such as aeration and carbon-source dosing during the denitrification phase. In the actual layout of WWTPs, the process type and treatment scale must match local wastewater treatment volume, water quality, treatment standards, and external environmental conditions to balance emission-mitigation requirements, cost effectiveness, and social development.

4 Discussion

4.1 Comparisons with previous studies

EF selection and the differences in source-data ranges introduce significant variations across studies. To provide a robust baseline for comparison, previous studies quantifying CH₄ and N₂O emissions from WWTPs via the EF approach were summarized and compared with our empirical findings (Table 3).

Notably, most scholars derived the EFs from the literature. However, several scholars [17,27] used the mean value from multiple studies, while some [29] used the median value of multiple studies. Several others [2] derived their EFs through fitting using Monte Carlo simulations. Beyond EF selection, the differences in WWTP numbers considered for the estimation and the accounting boundary also represent critical drivers of significant discrepancies observed in the results. Regarding the accounting units, the number of WWTPs surveyed varies significantly. For instance, Yan et al. [16], Du et al. [2], and this study calculated emissions from 3362, 5155, and 4550 WWTPs, respectively. Regarding accounting boundaries, most existing studies focused on direct emissions from operational wastewater treatment processes. Conversely, Du et al. [2] and Ministry of Ecology and Environment of the People's Republic of China [30] covered comprehensive, full-process emissions across the entire treatment cycle. Therefore, variations in metrics, such as EFs, WWTP numbers, and accounting boundaries collectively drive the substantial discrepancies observed in the published emission estimates.

Compared with previous studies, this study offers three distinct advancements. First, the long-time series dataset captures dynamic emission evolution throughout China's rapid urbanization and industrial restructuring. Second, the integrated approach—encompassing top-down and bottom-up methodologies—achieves an optimal balance between macrolevel consistency and microscale accuracy, thereby min-

imizing accounting uncertainties caused by data deviations. Third, distinguishing between domestic and industrial wastewater streams, alongside the A/O processes in the EF database, will clarify the distinctions in non-CO₂ GHG emissions driven by different wastewater sources and treatment processes.

4.2 Uncertainty analysis

Accounting methods based on activity levels and EFs inevitably introduce uncertainties. Du et al. [31] reported that the uncertainty margin of China's statistical data ranges from $\pm 5\%$ to $\pm 10\%$. Furthermore, expert estimation places the uncertainty of China-specific EFs at $\pm 15\%$ [32]. Concurrently, the IPCC 2019 Guidelines estimate the uncertainty range of global default EFs to be $\pm 30\%$.

To quantify the cumulative uncertainty of the emission inventory, we conducted a Monte Carlo simulation to propagate the uncertainties of key input parameters, specifically EFs, COD_{removal}, and TN_{removal}, to the final emission estimates. Within this framework, the probability density functions of all input parameters follow the log-normal distribution. The EFs employed in the calculation formulas for CH₄ and N₂O emissions from domestic and industrial wastewater varied. Therefore, to reflect this variation, four emission-quantity types were statistically distributed through 5000 iterations. Detailed simulation steps, parameter settings (e.g., probability distribution and uncertainty ranges), and calculation algorithms are provided in the ESM.

We separately calculate the cumulative uncertainties of CH₄ and N₂O emissions from domestic and industrial wastewater streams in China across a 95% confidence interval within the 2000–2024 timeframe. The simulation results reveal that domestic wastewater exhibited the highest cumulative uncertainty of CH₄ emission among all evaluated categories. However, its uncertainty was only within the range of $\pm 1.27\%$ to $\pm 2.12\%$. Furthermore, the overall uncertainty of N₂O emissions in domestic wastewater ranges from $\pm 0.64\%$ to $\pm 1.08\%$,

Table 3 Parameters adopted in previous studies and the statistical results.

EF	Year	CH ₄ emissions (Tg)	N ₂ O emissions (Tg)	Ref.
Fixed value in the literature	2014	0.027	0.002	Yan et al. [27]
Fixed value in the literature	2020	0.042	0.019	Tong et al. [28]
Fixed value in the literature	2006–2019	0.024–0.069	0.010–0.018	Wang et al. [17]
Fixed value in the literature	2005–2020	0.029–0.044	0.026–0.051	Yang et al. [12]
Fixed value in the literature	2020	0.150	0.022	Li et al. [11]
Fixed value in the literature	2009–2016	0.035–0.070	0.001–0.006	Xi et al. [29]
Case-specific value	2009–2019	0.417–0.667	0.012–0.023	Du et al. [2]
IPCC default value	2018	2.908	0.113	MEE [30]
Fixed value in the literature + IPCC default value	2000–2024	0.426–2.741	0.027–0.109	This study

while those of CH₄ and N₂O emissions from industrial wastewater range from $\pm 0.72\%$ to $\pm 0.81\%$ and $\pm 0.67\%$ to $\pm 0.92\%$, respectively. These results indicate the high reliability of the emission inventory.

4.3 Limitations

Although this study provides a long-time-series, high-spatial-resolution inventory of CH₄ and N₂O emissions from Chinese WWTPs, offering crucial data support for targeted mitigation policies and synergistic pollution and carbon reduction in the sector, certain objective limitations remain.

Emission-factor limitations. EFs for industrial wastewater CH₄ and N₂O rely on aggregated national estimates owing to the lack of systematic field-measurement data across different Chinese industrial sectors (e.g., chemical, textile, and food processing). This data gap may introduce deviations in emission estimates for WWTPs receiving a high proportion of industrial influent.

Process-level data limitations. Due to the inaccessibility of detailed process-level operational parameters (e.g., aeration rates and hydraulic retention times) of individual WWTPs, this study only broadly classified treatment technologies into aerobic and anaerobic categories, without further distinguishing the specific impacts of key operational parameters on emissions.

Exclusion of indirect emissions. Our inventory focuses on direct CH₄ and N₂O emissions during wastewater treatment, ignoring indirect emissions (e.g., N₂O from nitrogen-rich sludge disposal and CH₄ from biogas combustion during anaerobic treatment). This may lead to the underestimation of the total non-CO₂ GHG emissions from the wastewater treatment sector.

5 Conclusions

This study established a $0.1^\circ \times 0.1^\circ$ spatial-resolution emission inventory for CH₄ and N₂O emissions from Chinese WWTPs (2000–2024) utilizing an integrated framework that couples top-down and bottom-up methodologies. The key findings and policy implications are summarized below:

Spatiotemporal-emission characteristics. Non-CO₂ GHG emissions from China's WWTPs exhibited an initial growth trend, followed by stabilization, with domestic wastewater emerging as the primary source. Spatially, emission hotspots expanded from eastern China in 2000 to most provinces in north, central, and east China by 2024.

Super-emitter contribution. The top 10% of WWTPs contributed around 60% of the national CH₄ and N₂O emission estimates, with significant geographic agglomeration. Prioritizing the governance of these super-emitters provides a cost-effective pathway toward synergistic pollution mitigation and carbon abatement in the sector.

Key emission drivers. Wastewater treatment process technologies and plant scale were confirmed as the core controllable drivers of emission intensity. Anaerobic processes displayed sevenfold higher CH₄ emission intensity than aerobic processes, whereas N₂O emissions were dominated by influent nitrogen concentration with low correlation to process type. These findings imply the necessity of differentiated mitigation strategies: CH₄ control must focus on process optimization and super-emitting-source management, while N₂O control must target nitrogen-source reduction.

This study presents the spatiotemporal profiles of non-CO₂ GHG emissions from WWTPs, reveals the spatial-clustering characteristics of super-emitting sources, and clarifies the influence of internal controllable factors, such as process technologies and plant scale, on the emission intensity. The data in this list can provide a scientific basis for countries and regions to formulate precise emission-mitigation policies. The identification of super-emitting sources and differentiated control strategies offers a cost-effective and highly reliable implementation path for industries to synergistically achieve pollution mitigation and carbon-emission reduction. These insights are of profound practical significance for driving the green transition of China's wastewater treatment sector and accelerating global non-CO₂ GHG emission-mitigation efforts.

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None.

Author contribution statement

Huiwen Yang: Data curation, Formal analysis, Methodology, Visualization, Writing – review & editing.

Yue Zhu: Investigation.

Xu Zhao: Conceptualization, Funding acquisition, Project administration, Resources, Supervision.

All the authors contributed to Writing – original draft and have approved the final manuscript.

Data availability

All data used in this study are publicly available or can be obtained from official institutions, with the detailed access links and channels listed below:

Urban Drainage Statistical Yearbook: available from the official website of the Society of Chinese Urban Water Supply and Drainage (<https://cuwa.org.cn/>)

China Environmental Statistical Yearbook: available from the National Bureau of Statistics of China and the Ministry of Ecology and Environment of China (<https://www.mee.gov.cn/>)

Derived emission inventory dataset (from 2000 to 2024, $0.1^\circ \times 0.1^\circ$ grid): submitted as supplementary data and will be stored in the Figshare open database for public access

(<https://doi.org/10.6084/m9.figshare.32347614>)

Declaration of competing interest

All the contributing authors report no conflicts of interest in this work.

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Use of AI statement

During the preparation of this work, the authors used artificial intelligence tools in order to polish and refine the language expression of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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