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Carbon Emission Characteristics and Reduction Pathways in Urban Wastewater Treatment Plants: A Case Study of China

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Abstract. Urban wastewater treatment plants are a non-trivial source of carbon emissions. To characterize and reduce those emissions in practice, we quantified plant-level profiles, isolated the dominant sources, and designed staged mitigation pathways. We first screened 54 plants across China, then selected seven representative facilities—spanning heterogeneous grid mixes and treatment trains—for in-depth case analysis. Using a comprehensive accounting framework aligned with IPCC guidance and sector standards, we covered electricity use, chemical consumption, and direct releases of CH_4 and N_2O. Across the seven cases, carbon-emission intensity—total CO_2-equivalent per cubic meter of treated water—ranged from 0.333 to 0.956 kg CO_2e/m^3 (mean 0.550 kg CO_2e/m^3). Electricity use emerged as the largest contributor (on average 40% of total emissions), with intensity modulated by regional grid structure and by process configuration. Advanced treatment trains improved effluent quality yet raised energy demand and associated emissions. By contrast, plant form (above-ground vs. underground) was not determinative; structural effects can be offset where clean energy adoption and operational tuning are in place. Reaching carbon-neutral operation therefore calls for an integrated strategy and a phased rollout. We center the roadmap on three measures: (i) unlocking energy-saving potential through equipment modernization, (ii) enabling precise emission control via advanced process optimization, and (iii) facilitating renewable substitution through on-site energy recovery. Together, these steps support a transition from high-energy treatment facilities toward low-carbon, energy-symbiotic systems.

Keywords: Wastewater treatment, Carbon emissions, Carbon neutrality, Emission reduction pathways

1. Introduction

The current global climate situation is increasingly severe. The IPCC Sixth Assessment Report (AR6) indicates that human activities have caused global surface temperatures to rise by approximately 1.1°C above pre-industrial levels [1]. Even more concerning, the latest assessment by the United Nations Environment Programme [2] warns that if countries maintain only their current commitments, global warming could reach 2.5–2.9°C by the end of this century, severely jeopardizing the 1.5°C temperature control target set by the Paris Agreement. To address climate change and global warming more effectively, China has introduced the “dual carbon” strategy,

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which sets explicit carbon reduction targets for key sectors. Among these, urban wastewater treatment facilities—as energy-intensive infrastructure—possess significant untapped potential for emissions reduction. According to data from China's Fourth Biennial Update Report on Climate Change [3], wastewater and waste treatment account for only about 2% of total national emissions, yet the sector is characterized by high energy consumption intensity. This "low total volume, high intensity" emission profile, combined with the potential for substantial reductions through low-carbon technologies and management practices, makes the wastewater sector a valuable model for decarbonizing other industries.

A consensus has emerged in academia that carbon emissions from wastewater treatment are multidimensional, originating from three main sources: (1) emissions of CH_4 and N_2O from biochemical processes, (2) indirect emissions from equipment operation, and (3) embedded emissions from chemical usage [4] The "three-source-driven" theoretical framework proposed by Hao et al. [5] has provided a foundational structure for related research. Within this framework:

(1) Direct emissions mainly arise from biological treatment processes, where CH_4 is produced under anaerobic conditions and N_2O is generated as a by-product of denitrification. It is important to note that despite its lower volumetric emission, N_2O has a global warming potential 273 times that of CO_2 over a 100-year time horizon [1], making its control paramount.

(2) Indirect emissions primarily result from electricity consumption, with a significant portion attributable to aeration systems. Preliminary research indicates that in typical activated sludge processes, aeration units can account for more than 60% of a plant's total electricity use. Embedded emissions from chemical consumption are also notable in certain treatment processes.

In addition to controlling the three aforementioned emission sources, enhancing carbon sink potential represents an important complementary direction for emission reduction, mainly through biogas recovery and renewable energy utilization. For example, the Beijing Huaifang Wastewater Treatment Plant has demonstrated that optimizing biogas utilization and installing photovoltaic systems can achieve 15–40% energy self-sufficiency [6].

Despite notable advances, several issues remain open. (i) Carbon accounting still lacks a common standard, most visibly in the divergent emission factors used for CH_4 and N_2O. (ii) Many reduction efforts are technology-by-technology fixes rather than system-level optimization. (iii) Evidence tailored to China's water-quality regimes and operating models is thin, which limits how far overseas experience can be localized.

Against this backdrop, we trace the principal emission pathways in municipal wastewater treatment, using the representative Chinese plants selected for analysis. Through material-flow analysis, we apportion total emissions to specific pathways and, in doing so, provide a data-grounded basis for ranking priorities and shaping targeted mitigation. Building on those results, we outline a phased decarbonization route to guide the sector's transition toward lower-carbon operation.

2. Research methodology

2.1. Case study overview

Fifty-four wastewater treatment plants nationwide were selected, spanning diverse geographic regions and construction types (both above-ground and underground). The treatment capacities of these plants ranged from 1,500 to 700,000 m^3 per day. As the cases primarily involved newly built, expanded, or upgraded facilities, they collectively reflect current industry trends focused on improving effluent quality and advancing low-carbon operations. Moreover, the diversity of

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treatment processes and discharge standards within the sample enables comparative analysis across different regions and technologies.

2.2. Carbon emissions calculation

Carbon emission accounting in this study follows the IPCC 2019 Guidelines, the TCUWA 50055-2023 Standard for Estimating Carbon Emission Reductions in Urban Sewage Treatment Plants [7], and recommended values from relevant literature. The system boundary is defined as the entire on-site treatment process, encompassing primary wastewater treatment, chemical addition, sludge treatment and disposal, and energy recovery.

(1) Carbon Emission Intensity from Electricity Consumption

Electricity emissions can be calculated using the factor method, expressed as follows:

$$CE_{electricity} = \frac{E_{electricity} \times EF_{electricity}}{D \times 10000} \quad (1)$$

Where, CEeletricity is Carbon emissions from electricity consumption of operational equipment in the wastewater treatment segment, kg CO_2/m^3; Eelectricity is the total electricity consumption of operational equipment in the wastewater treatment segment, kWh/d;EFelectricity is the emission factor for electricity generation, kgCO_2/kWh;Q is the average inflow volume on day m at the wastewater treatment plant, m^3.

(2) Chemical Consumption Carbon Emission Intensity

Where, CEchemical is the carbon emissions from chemical consumption during wastewater treatment, kgCO_2/m^3; Echemcial,i is the consumption of i^{th} chemical reagent, unit/d;

EFchemcial,i is the emission factor of i^{th} chemical reagent, kgCO_2/unit; Q is the average inflow volume on day m at the wastewater treatment plant, m^3.

(3) Emission intensity of CH4

Emission intensity of CH4 can be calculated as follow.

$$CE_{\mathrm{CH_4}} = \frac{\left[\mathrm{Q} \times (\mathrm{COD}_{in,m} - \mathrm{COD}_{out,m}) \times \mathrm{EF}_{\mathrm{CH_4}} \times \mathrm{GWP}_{\mathrm{CH_4}} \times 10^{-3} + \mathrm{Mp} \times \mathrm{GWP}_{\mathrm{CH_4}}\right]}{\mathrm{Q}} \quad (2)$$

Where, CECH₄ is equivalent emission intensity from methane generated during wastewater treatment, kg CO_2eq/m^3;Q is the average inflow volume on day m at the wastewater treatment plant, m^3;$COD_{in,m}$ is average influent COD concentration on day m, mg/L;$COD_{out,m}$ is average effluent COD concentration on day m, mg/L;EF_{CH_4} is CH_4 emission factor, kg CH_4/kg COD, conventionally recommended range 0.0040-0.0075; higher value is used when sludge accumulation exists in structures;M_p is CH_4 emissions from lift pumps and screen chambers on day m, kg; GWP_{CH_4} is the global warming potential of CH_4, 28.

(4) Emission intensity of N2O

Emission intensity of N2O can be calculated as follow.

$$CE_{N_2O} = \mathrm{Q} \times \left(\mathrm{TN}_{in,m} - \mathrm{TN}_{out,m}\right) \times \mathrm{EF}_{\mathrm{w-N_2O_4}} \times 44/28 \times \mathrm{GWP}_{N_2O} \times 10^{-3} \quad (3)$$

Where, CEN₂O is equivalent emissions of N_2O from the treatment section on day m, kg CO_2eq/m^3;Q is the average inflow volume on day m at the wastewater treatment plant, m^3;$TN_{in,m}$ is average influent TN concentration on day m, mg/L;$TN_{out,m}$ is average effluent TN concentration on

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day m, mg/L;EF_{N2O} is N_2O emission factor for wastewater treatment, kg N_2O-N/kg N;44/28 is conversion factor, kg N_2O/kg N_2O-N;GWP_{N2O} is the global warming potential of N_2O, 265.

(5) Total Carbon Emission Intensity

Total carbon emission intensity can be calculated as follow.

$$CE_{total} = CE_{electricity} + CE_{chemical} + CE_{CH4} + CE_{N2O} \quad (4)$$

Where, CE total is total Emission intensity, $kgCO_2eq/m^3$;CEeletricity is Carbon emissions from electricity consumption of operational equipment in the wastewater treatment segment, kg CO_2/m^3;

CEchemical is the carbon emissions from chemical consumption during wastewater treatment, kg CO_2/m^3, $CECH_4$ is equivalent emission intensity from methane generated during wastewater treatment, kgCO2eq/m³; CE_{N2O} is equivalent emissions of N_2O from the treatment section on day m, $kgCO_{2eq}/m^3$.

3. Results and discussion

3.1. Overall carbon emissions analysis of representative cases

This study analyzed the carbon emission characteristics of seven wastewater treatment plants as representative cases. As shown in Figure 1, the carbon emission intensity per unit of treated water for these plants ranges from 0.333 to 0.956 kg CO_2/m^3, with an average of approximately 0.550 kg CO_2/m^3. This range is broadly consistent with levels reported in the international literature [8,9], although significant variation exists among individual plants.

Geographic contrasts are pronounced: southern provinces tend to exhibit lower carbon-emission intensities than the north. In Yunnan, the representative plant reports 0.333 kg CO_2/m^3, whereas sites in Hebei and Shandong exceed 0.900 kg CO_2/m^3. The gradient largely tracks grid composition—hydropower-heavy Yunnan and Guangdong carry lower grid-emission factors, while coal-reliant Hebei and Shandong push intensities upward. In line with this pattern, provincial emission factors are 0.5978 in Jiangsu and 0.4403 in Guangdong, but only 0.1073 in Yunnan [10].

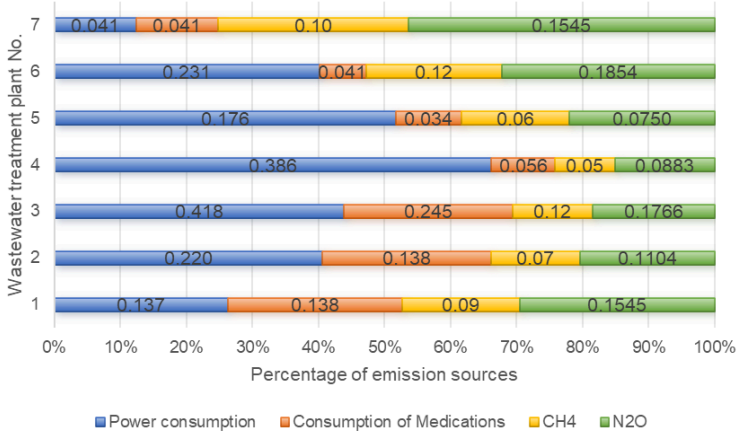


Figure 1. Emission of seven selected plants

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3.2. Impact of electricity consumption

Electricity use is the dominant lever in the carbon profile of wastewater treatment plants (WWTPs). In our accounting across seven facilities, electricity-related emissions span 12–66% of totals, with a central tendency near 40%. Plant No. 3 stands out: its electricity-emission intensity reaches 0.418 kg CO_2/m^3, nearly twice that of several plants in southern China.

Two forces drive this spread. First, grid composition: hydropower-heavy southern systems (e.g., Yunnan) carry lower emission factors, yielding less carbon-intensive electricity; coal-reliant grids in northern and eastern China, by contrast, push the per-kilowatt-hour footprint higher. Second, process energy demand: tighter nitrogen removal targets materially raise aeration loads. Plant No. 3, which cuts total nitrogen from 50 mg/L to <10 mg/L, necessarily consumes more aeration energy than Plants No. 1 and No. 2 in Jiangsu (influent TN 45 and 35 mg/L; effluent <10 mg/L), widening electricity-driven emission gaps.

These patterns argue for a dual decarbonization strategy for the electricity footprint of WWTPs. (i) Efficiency first: deploy variable-frequency blowers, fine-bubble aeration, and intelligent dissolved-oxygen control to lower unit energy consumption. (ii) Substitution where feasible: tailor on-site renewables—photovoltaics and biogas utilization—to local conditions to cut grid dependence and curb emissions at the source.

3.3. Impact of plant configuration

Configuration nudges energy use in WWTPs but does not, by itself, dictate the carbon outcome. Underground facilities, in principle, carry extra loads for ventilation, lighting, and lift pumping [11]. Yet our evidence points away from configuration as a decisive lever. Plant 5—an underground site—posts a total emission intensity of ≈0.340 kg CO_2/m^3, the second-lowest among the seven plants and well below several above-ground peers. Building form adds ancillary demand; it does not set the emissions ceiling.

Two forces explain the gap. First, regional grid factors: a cleaner power mix at Plant 5's location offsets the ancillary energy penalty. Second, operations: energy-saving practices plausibly lift overall efficiency, narrowing (or reversing) the disadvantage of underground layouts.

The practical reading is cautious: ancillary consumption is an operational tax for underground plants, but overall emissions are shaped jointly by energy mix, influent/effluent quality targets, process parameters, and management strategy. Design and operations should therefore account for ancillary loads without over-weighting configuration in isolation. Looking ahead, comparative analyses grounded in actual operating data—contrasting underground and above-ground facilities across scales and regions—are needed to yield conclusions with broader applicability.

3.4. Impact of wastewater treatment process

Process choice—and how unit operations are stitched together—largely sets a WWTP's carbon budget. Different treatment trains tilt the balance between indirect emissions (electricity, chemicals) and direct biogenic releases by shaping energy demand, reagent use, and the biochemical environment.

To achieve deep nitrogen and phosphorus removal, most case plants adopt multi-stage schemes of pretreatment → biological treatment → advanced treatment. Our results show a clear penalty from layering on advanced units. A like-for-like comparison in Jiangsu makes this explicit: Plant 1 (oxidation ditch + high-efficiency sedimentation tank + denitrification filter) versus Plant 3 (AAO +

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MBR + denitrification filter + dissolved-air flotation). The added MBR and flotation stages at Plant 3 drive daily electricity use to 21,000 kWh, yielding an electricity-based carbon intensity of 0.418 kg CO_2/m^3—over 3× that of Plant 1 (0.138 kg CO_2/m^3). In short, process complexity buys effluent quality at a tangible carbon cost; selection should therefore weigh water-quality gains against the associated energy and emissions burden.

Chemically intensive routes add a second, embedded source of emissions. In plants targeting deep phosphorus removal, reagent dosing becomes non-trivial. Plants 5 and 6 employ magnetic coagulation, consuming 508 kg/d and 500 kg/d of magnetic powder, respectively, alongside large PAC additions (e.g., 6,000 kg/d at Plant 5). For Plant 6, the calculated chemical-related emission intensity is 0.0406 kg CO_2/m^3. Although below the electricity component, this share is material. Consequently, process evaluation must extend beyond kilowatt-hours to the life-cycle carbon of reagents—particularly for dosing-heavy options such as coagulation and chemical phosphorus removal.

3.5. Carbon neutrality pathway analysis

Low-carbon performance in wastewater treatment is won earliest—at the source—and sustained through coordination across unit processes. Three priorities follow. First, adopt high-efficiency biological nitrogen-removal routes that keep external carbon demand to a minimum. Second, deploy smart-water controls to tune aeration and chemical dosing in real time, matching process needs rather than design maxima. Third, integrate energy-recovery steps—most notably anaerobic sludge digestion for biogas—so that treatment and power generation reinforce one another. Taken together, these moves assemble an integrated system that safeguards effluent quality, recovers usable energy, and lowers the carbon bill—a practical water-quality–energy–carbon nexus rather than a set of siloed upgrades.

3.5.1. Equipment upgrades

Targeted retrofits deliver quick carbon wins. Replacing legacy assets with high-efficiency equipment can trim electricity use by 15–30% [12]. In practice, (i) intelligent variable-frequency blowers enable load-responsive aeration, cutting aeration energy by ≈30%; (ii) high-efficiency permanent-magnet motor pumps typically save 15–25% relative to conventional units; and (iii) advanced microporous aeration devices raise oxygen-transfer efficiency to 30–40%.

The case for upgrades is clearest where electricity dominates the footprint. Plant No. 3 in Jiangsu, with an electricity-related carbon intensity of 0.418 kg CO_2/m^3, is constrained by aeration demand. A coordinated retrofit—variable-frequency blowers plus high-efficiency pumps—would lower overall electricity use by 15–30% [12], corresponding to an ≈120 t CO_2-eq/yr reduction [13]. The payoff is even stronger on grids with high emission factors, as in much of northern and eastern China, where each saved kilowatt-hour avoids more carbon at the source.

3.5.2. Precision control of water treatment processes

Meeting tight effluent limits—especially TN < 10 mg/L—often drives WWTPs into high-intensity aeration, as seen at Plants 1, 2, and 3 (Jiangsu), with predictable energy penalties. A shift to intelligent, load-responsive control changes that profile. By coupling real-time influent and water-quality signals with closed-loop dissolved-oxygen (DO) regulation, plants can avoid chronic over-aeration and trim aeration electricity by ≈5–15% while holding nitrification performance steady.

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The same principle extends beyond air. In advanced trains—notably the magnetic coagulation used at Plants 5 and 6—chemical dosing carries a non-trivial embedded carbon cost. Integrated control architectures fuse online analytics (e.g., ammonia, nitrate, orthophosphate) with supervisory logic to coordinate DO set-points, carbon-source addition, and phosphorus-removal agents. In practice, this yields 10–20% cuts in chemical consumption without relaxing effluent targets, directly lowering the life-cycle footprint attributable to reagent manufacture and transport.

Operations, not hardware alone, decide the bill. The aeration system—the site's most energy-intensive unit—offers the fastest win when instrumented correctly. At Plant No. 3, where stringent denitrification squeezes the process envelope, an intelligent aeration layer equipped with online ammonia and nitrate sensors can modulate blower output in real time, keeping DO in a tight optimal band. Field experience indicates 10–25% reductions in aeration energy are achievable under such control [14]. Likewise, for chemical-intensive steps, a smart dosing system tied to online phosphorus analyzers and combining feedforward + feedback keeps PAC addition precise—meeting effluent specs without chronic overdosing and cutting the embedded-carbon share at its source.

3.5.3. Energy and resource recovery

The successful integration of renewable energy at Beijing's Huai Fang Wastewater Treatment Plant demonstrates the potential to achieve 15–40% energy self-sufficiency [6]. This highlights that enhancing energy autonomy and promoting resource circularity are essential strategies for wastewater treatment plants to mitigate carbon emissions and progress toward carbon neutrality.

Wastewater treatment plants often feature extensive rooftop areas, unused land, and open water surfaces, providing ideal conditions for photovoltaic system installation. For example, Plants 1, 2, and 3—located in eastern China—benefit from abundant solar irradiation and are connected to a regional grid with a relatively high carbon emission factor (0.597 kg CO_2/kWh). Deploying photovoltaic systems in such contexts can effectively offset grid electricity derived from high-carbon sources, resulting in substantial emission reductions.

Treated effluent provides a stable thermal source and sink due to its consistent flow and limited seasonal temperature variation. Water-source heat pumps can extract thermal energy from effluent to supply heating and cooling for on-site administrative buildings. This approach replaces conventional gas boilers and individual air-conditioning units, thereby eliminating direct emissions from fossil fuel combustion and indirect emissions associated with high-global-warming-potential refrigerants. This technology is particularly suitable for wastewater treatment plants in northern China that require space heating.

Sludge treatment constitutes a critical discharge process in wastewater treatment plants. Currently, sludge drying, incineration, and biomass conversion technologies are increasingly adopted. Proper resource recovery of sludge not only reduces carbon emissions from conventional disposal methods (e.g., landfilling) but also converts sludge into energy or fertilizer, enabling waste recycling. This approach simultaneously lowers carbon emissions and generates economic benefits. For example, at Plant No. 5, which produces substantial sludge volumes, anaerobic digestion is prioritized. This process converts organic matter in sludge into biogas (primarily methane). After purification, the biogas can be used for power generation or heat production, achieving "energy from waste." The resulting digested sludge, after further drying, can serve as auxiliary fuel for waste incineration plants, or as a substitute raw material in cement kilns, enabling energy recovery. Alternatively, after stabilization treatment, it can be used as landscaping soil or a soil conditioner, completing the nutrient cycle.

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On the reuse side, high-quality effluent—especially from advanced steps such as denitrification filters or MBR—can be diverted to non-potable municipal services, industrial cooling loops, or ecological river replenishment. Reuse directly displaces freshwater withdrawals, which in turn eases the plant's overall energy demand and trims the carbon attributable to raw-water extraction. The result is a tighter, more efficient system: water quality is maintained, while the energy and emissions burden is reduced.

4. Conclusion

Across seven representative plants spanning different regions, our carbon accounting traces a wide performance envelope. Carbon-emission intensity ranges from 0.333 to 0.956 kg CO_2/m^3 (mean 0.550 kg CO_2/m^3). The spread is not random: it mirrors regional grid carbon intensity, the process complexity required to meet tight effluent standards, and day-to-day operational management.

Electricity remains the dominant lever. Indirect, electricity-related emissions average ≈40% of totals and span 0.041–0.419 kg CO_2/m^3, reflecting the interaction between local energy mixes and process energy demand. Process selection matters as well. Meeting stricter discharge limits typically pulls in advanced units (e.g., MBR, denitrification filters) that raise energy use—and thus emissions. Chemically intensive routes (e.g., magnetic coagulation) add a second, embedded burden through reagent consumption; those carbon implications must be priced into process choice.

Emissions emerge from interacting factors, not a single design decision. Case evidence shows that although underground plants (e.g., Plant No. 5) carry extra ancillary loads, cleaner regional grids and tuned operations can hold net emissions down; architecture alone is not decisive.

Taken together, the path to carbon neutrality is systemic, not a one-technology fix. Effective strategies should couple equipment upgrades (energy conservation), intelligent process control (efficiency gains), and on-site energy recovery (resource looping). Carbon management needs to be embedded end-to-end—from planning and design, through technology selection, into operations and maintenance—to shift WWTPs from high-energy incumbents toward low-carbon, environmentally symbiotic systems.

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