

Article

Research on Carbon Emission Accounting of Municipal Wastewater Treatment Plants Based on Carbon Footprint

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Abstract

In the context of global carbon neutrality, municipal wastewater treatment plants (WWTPs), as key sources of greenhouse gas emissions, urgently require quantification of carbon emissions and implementation of mitigation strategies. This study establishes a life-cycle carbon footprint model encompassing the stages of pretreatment, biological treatment (AAO process), and sludge treatment, with integrated consideration of municipal sewer networks. Key findings reveal the following: The biological treatment stage contributes 68.14% of total carbon emissions. N₂O (nitrous oxide), due to its high global warming potential (GWP), is the primary source of direct emissions (0.333 kg CO₂eq/m³). In the pretreatment stage, 80.4% of carbon emissions originate from the electricity consumption of sewage lifting pump stations (0.030 kg CO₂eq/m³). During the sludge treatment stage, carbon emissions are concentrated in residual sludge lifting (0.0086 kg CO₂eq/m³) and sludge dewatering/pressing (0.0088 kg CO₂eq/m³). Accordingly, this study proposes the following mitigation strategies: novel nitrogen removal processes should be implemented to optimize aeration control and enhance methane (CH₄) recovery during the biological period, and variable frequency drive (VFD) pumps and IoT (Internet of Things) technologies should be employed to reduce energy consumption during the pretreatment period, and during the sludge treatment period, low-carbon dewatering technologies should be adopted. This work provides a theoretical foundation for process-specific carbon management in WWTPs and facilitates the synergistic advancement of environmental stewardship and dual-carbon objectives through technology–system integration.

Keywords: carbon footprint; WWTPs; anaerobic-anoxic-oxic (AAO); carbon accounting; carbon mitigation



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1. Introduction

Since China proposed the “dual carbon” goal [1], high-carbon emission industries such as energy and transportation have accelerated their low-carbon transition. As a critical component of urban infrastructure, wastewater treatment systems have become a significant anthropogenic source of greenhouse gas emissions. Data indicates that approximately 9% of global methane (CH₄) and 3% of nitrous oxide (N₂O) emissions originate

from wastewater treatment activities [2]. In China, CO₂ emissions from wastewater treatment surged from 13.34 million tons in 2005 to 53 million tons in 2019 [3,4]. Although the IPCC Guidelines exclude microbially metabolized CO₂ from accounting, studies reveal that around 28% of organic carbon in wastewater derives from fossil carbon sources. The CO₂ emissions from this source account for 13% of total CO₂ emissions, and can reach as high as 23% under specific conditions. Despite the exclusion of these CO₂ emissions from the IPCC's National Greenhouse Gas Inventory Guidelines, considerable debates persist in academia regarding their inclusion in total emissions to enable more accurate carbon assessment [5–7]. Currently, many carbon accounting methods in the literature are based on IPCC 2006 or IPCC 2019 guidelines, but some scholars have identified significant accounting errors associated with these approaches [8,9]. Consequently, there is growing interest in developing carbon accounting methodologies for wastewater treatment plants (WWTPs) that align with the needs of national strategic development. For instance, Xi et al. [10] conducted a comparative analysis of 50 WWTPs in Shanghai using the Operational Data Integration Method (ODIM) alongside IPCC 2006/2019 guidelines. Liao et al. [11] and Chen et al. [12] utilized LCA to assess the carbon footprint of WWTPs employing different treatment processes. Qiu et al. [13] utilized the emission factor method to account for carbon emissions in urban WWTPs across China's five major city clusters, analyzing the spatio-temporal distribution and influencing factors of greenhouse gas emissions. Bao et al. [14] employed direct measurement methods to quantify on-site CO₂ emissions from WWTPs. Shrestha et al. [15] used Python programming to estimate the GHGs emissions from the domestic wastewater sector in Nepal under various technological development scenarios for 2020 to 2040 using the refined 2019 estimation methodology developed by IPCC. Maziotis and Molinos-Senante [16] employed the Efficiency Analysis Tree (EAT) method to account for carbon emissions in 109 WWTPs in Spain. Corominas et al. [17] applied both static and dynamic prediction models to simulate carbon emission processes in WWTPs, finding that dynamic models could capture fluctuations influenced by parameters such as temperature and C/N ratio, whereas static models failed to reflect such variations. Despite these advances, existing accounting methods primarily focus on total carbon emissions at the plant level and generally lack unit-level carbon emission data. This limitation hinders the ability to provide specific or targeted recommendations for carbon reduction strategies within individual treatment units of WWTPs.

Based on the current reality that AAO wastewater treatment processes account for over 60% of China's market share [18], this study focuses on an AAO wastewater treatment plant in Hunan Province. It incorporates direct carbon emissions from municipal sewer networks into the accounting framework, establishing a comprehensive carbon footprint and emission quantification model spanning the entire "sewer network-wastewater treatment-sludge disposal" chain. The wastewater treatment process is categorized into three distinct stages: (1) pretreatment stage, centered on sewage lifting pump stations and vortex grit chambers, while extending to incorporate municipal sewer networks; (2) biological treatment stage, identified as the primary carbon emission source during treatment, encompassing facilities such as aeration tanks, secondary sedimentation tanks, and disinfection units; and (3) sludge treatment stage, comprising sludge thickening and dewatering, filtering pressing, and off-site transportation. This study establishes a theoretical framework for both unit-level carbon emissions accounting and targeted carbon management within wastewater treatment plants (WWTPs). It offers guidance for implementing specific and targeted carbon reduction measures in WWTPs operations, thereby promoting synergistic progress between environmental benefits and the achievement of "dual-carbon" goals.

2. Material and Methods

2.1. Basic Information on Municipal WWTPs Investigated

The wastewater treatment plant selected for this study, which employs an AAO process, is located in Hunan Province, China. This facility operates with a daily treatment capacity of $2.0 \times 10^5 \text{ m}^3/\text{d}$. It serves a total catchment area of 72.7 km^2 and a population of 486,200 residents. The operational parameters for the influent and biological treatment stages, along with influent/effluent water quality data, are detailed in Table 1. The effluent discharge complies with the Class 1A standards specified in China's Discharge Standard of Pollutants for Municipal Wastewater Treatment Plants (GB 18918-2002) [19]. The sludge treatment process primarily involved gravity thickening followed by dewatering using a belt filter press (SIE BT-PRESS 4000, Speyer, Germany). The characteristic flows within the sludge treatment stage—specifically, the influent sludge volume and the volume of dewatered sludge discharged from the plant—are presented in Table 1.

Table 1. Water quality of influent and effluent as well as operational parameters of the WWTP in Hunan Province (Jan–Dec 2023).

Phase	Operation Parameters		Concentration of Pollutants			
	Influent (m^3/d) Range (Mean)	Effluent (m^3/d) Range (Mean)	COD (mg/L) Range (Mean)	BOD ₅ (mg/L) Range (Mean)	TN (mg/L) Range (Mean)	TP (mg/L) Range (Mean)
Pretreatment stage	177,866–234,429 (205,551)	—	169.67–270.17 (205.84)	85.02–108.16 (100.14)	14.43–19.59 (16.45)	2.13–3.73 (2.78)
Biological treatment stage	—	169,576–198,477 (184,352)	12.19–15.98 (13.82)	2.61–4.89 (3.73)	6.88–9.23 (7.78)	0.17–0.28 (0.23)
Sludge treatment stage	3224–4627 (3952)	58.7–68.4 (65.6 moisture content 78%)	—	—	—	—

2.2. System Boundary of the Case Study

The carbon accounting boundary for the wastewater treatment plant extends beyond the facility to include municipal sewer networks (Figure 1). Conventionally, carbon emission accounting commences when wastewater enters the treatment plant. However, this approach overlooks greenhouse gases (CO_2 , CH_4 , and N_2O) generated through microbial activity within municipal sewer systems [20]. Consequently, to enable more accurate assessment of carbon emissions from wastewater treatment plants, the accounting scope must incorporate this sewer network.

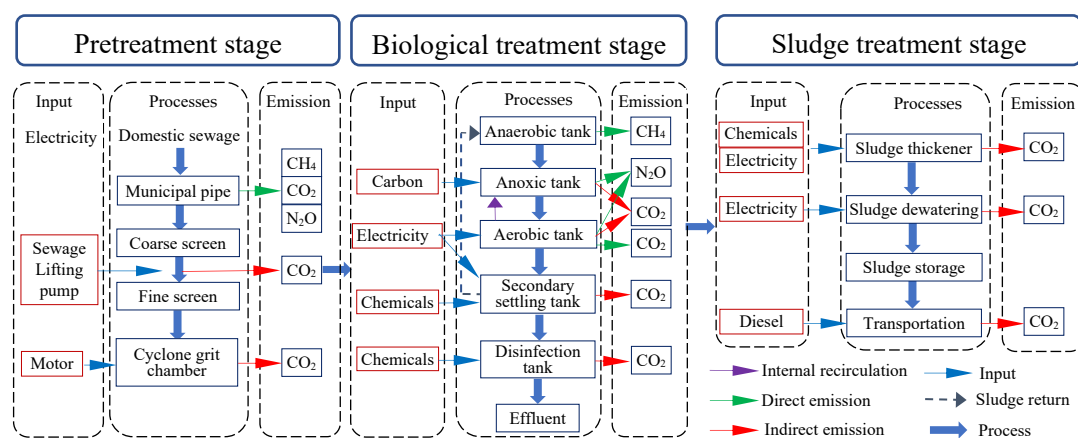


Figure 1. The boundary of accounting: from municipal sewage network to the wastewater treatment plant (pretreatment stage, biological treatment stage, and sludge treatment stage).

2.3. Carbon Emission Calculation in the Pretreatment Stage

2.3.1. Direct Carbon Emissions and Emission Intensity

The preliminary treatment stage extends from the municipal sewer network to the cyclone grit chamber. The carbon emission sources within this stage, as illustrated in Figure 1, primarily comprise direct and indirect carbon emissions. Direct carbon emissions arise predominantly from CO₂ generated by the aerobic microbial degradation of fossil-derived carbon in wastewater within sediments of the municipal sewer network [21], and CH₄ and N₂O produced by anaerobic metabolism of organic matter in biofilms attached to pipe walls and by microorganisms within the pipelines [22,23]. These emissions exclude biogenic CO₂ of biological origin, which constitutes a carbon-neutral flux since it originates from—and ultimately returns to—the atmospheric carbon pool without contributing to net atmospheric CO₂ increase. Indirect carbon emissions are mainly attributable to CO₂ emissions resulting from the electricity consumption required to operate the hydraulic lift pump station located after the coarse screens and the cyclone grit chamber within the wastewater treatment plant. The calculation methodologies for the emission quantities of these three greenhouse gases (CO₂, CH₄, N₂O) originated from the municipal sewer network are detailed in Equations (1)–(3).

$$m_{CO_2f1,i} = F_{CF} \times EF_{CO_2} \times C \times \beta \times Q_{0,i} \quad (1)$$

$$m_{CH_4f1,i} = EF_{CH_4} \times C \times \beta \times Q_{0,i} \quad (2)$$

$$m_{N_2Of1,i} = EF_{N_2O,PE} \times PE \quad (3)$$

$m_{CO_2f1,i}$: the fossil-derived CO₂ emissions (kg CO₂) from the municipal sewer network on day i . F_{CF} : the fossil carbon fraction for CO₂ emissions, set at 12% [7]. EF_{CO_2} : the CO₂ emission factor for the municipal sewer network (kg CO₂/kg COD_{cr}), with the value of 0.0124 kg/kg. β : the COD_{cr} degradation coefficient, with the value of 0.6 [24]. C : the average concentration of organic matter in the wastewater within the municipal sewer network (expressed as COD_{cr}), kg/m³. $Q_{0,i}$: the wastewater flow volume conveyed through the sewer network on day i , m³. $m_{CH_4f1,i}$: the CH₄ emissions (kg CH₄) from the municipal sewer network on day i . EF_{CH_4} : the CH₄ emission factor for the municipal sewer network (kg CH₄/kg COD_{cr}), with the value of 0.00105 kg/kg. $m_{N_2Of1,i}$: the N₂O emissions (kg N₂O) from the municipal sewer network on day i . $EF_{N_2O,PE}$: the per capita N₂O emission factor, which adopts the IPCC default emission factor for N₂O from wastewater discharged to aquatic environments, specifically 0.0035 kg/(person·year) [25]. PE : the served population, in number of persons.

The carbon emission intensity of a wastewater treatment plant (WWTP) refers to the amount of carbon emissions generated per unit volume of treated wastewater. It serves as a key metric for comparing carbon emissions across different WWTPs. The calculation formulas for the direct carbon emission intensity during the preliminary treatment stage are Equations (4)–(6).

$$E_{CO_2f1} = \frac{\sum_{i=1}^t m_{CO_2f1,i}}{\sum_{i=1}^t Q_{0,i}} \quad (4)$$

$$E_{CH_4f1} = \frac{\sum_{i=1}^t m_{CH_4f1,i} \times 28}{\sum_{i=1}^t Q_{0,i}} \quad (5)$$

$$E_{N_2Of1} = \frac{\sum_{i=1}^t m_{N_2Of1,i}}{\sum_{i=1}^t Q_{0,i}} \times 298 \quad (6)$$

E_{CO_2f1} : Fossil carbon emission intensity in municipal sewer networks, kg CO₂/m³. E_{CH_4f1} : CH₄ emission intensity in municipal sewer networks, kg CO₂eq/m³. E_{N_2Of1} : N₂O

emission intensity in municipal sewer networks, kg CO₂eq/m³. The values 28 and 298 represent the Global Warming Potentials (GWP) of CH₄ and N₂O, respectively [26].

2.3.2. Indirect Carbon Emissions and Emission Intensity

The indirect carbon emissions during the sewage pretreatment stage primarily originate from the electricity consumption during the operation process. This specifically includes the energy use of hydraulic lifting in wastewater pumping stations and mechanical agitation in vortex grit chambers. The calculation of carbon emissions at this stage is shown in Equation (7).

$$m_{ej,i} = W_{j,i} \times EF_e \quad (7)$$

$m_{ej,i}$: the carbon emissions (kg CO₂eq) resulting from electricity consumption under scenario j on day i , where $j = 1$ represents the operational scenario of the sewage pumping station at the wastewater treatment plant, and $j = 2$ represents the operational scenario of the aerated grit chamber. $W_{j,i}$: the electricity consumption (kW·h) under scenario j on day i . EF_e : Emission factor for the regional grid electricity, kg CO₂eq/(kW·h). The value for the Central China regional grid, 0.8587 kg CO₂eq/(kW·h), is selected [27].

The calculation of carbon emission intensity of electricity consumption during the preliminary treatment phase is in Equation (8).

$$E_{ej} = \frac{\sum_{i=1}^t m_{ej}}{\sum_{i=1}^t Q_{0,i}} \quad (8)$$

E_{ej} : Carbon emission intensity from electricity consumption for scenario j (kg CO₂eq/m³).

2.4. Carbon Emission Calculation in the Biological Treatment Stage

2.4.1. Direct Carbon Emissions and Emission Intensity

As the core of the AAO process, the biological treatment stage bears the key function of removing organic matter from municipal sewage. Consequently, the majority of direct carbon emissions (greenhouse gases such as CH₄, N₂O, and CO₂) are generated in this stage. Furthermore, this biological treatment stage also involves other forms of carbon emissions, as shown in Figure 1.

Figure 1 shows the sources of carbon emissions in the biological treatment stage: In the anaerobic tank, methanogens decompose organic acids, producing CH₄; In the anoxic tank, denitrifying bacteria reduce NO₃[−]/NO₂[−] to N₂ through a series of intermediate product conversions, accompanied by the generation of N₂O. Furthermore, when denitrification occurs in the anoxic tank, the insufficient carbon sources necessitate the addition of external carbon sources; this process also leads to indirect carbon emissions. In the oxide tank, organic matter decomposes due to aeration, producing fossil-derived carbon. Simultaneously, N₂O is released during the oxidation of ammonia and hydroxylamine [28]. The calculation of direct carbon emissions for this stage is shown in Equations (9)–(12).

$$m_{CH_4f2,i} = [Q_{1,i} \times (COD_{1,i} - COD_{2,i}) \times 10^{-3} - SG_i \times P_{v,i} \times \rho_s] \times EF_{CH_4} \quad (9)$$

$$EF_{CH_4} = B_0 \times MCF \quad (10)$$

$$m_{N_2Of2,i} = Q_{1,i} \times (TN_{1,i} - TN_{2,i}) \times 10^{-3} \times EF_{N_2O} \times C_{\frac{N_2O}{N_2}} \quad (11)$$

$$m_{CO_2f2,i} = [Q_{1,i} \times (COD_{1,i} - COD_{2,i}) \times 10^{-3}] \times F_{CF} \quad (12)$$

$m_{CH_4f2,i}$: CH₄ emissions on day i , kg CH₄. $Q_{1,i}$: Influent flow rate to the biological treatment stage on day i , m³. $COD_{1,i}$: Average influent COD_{cr} concentration in the bio-

chemical reaction tank on day i , mg/L. $COD_{2,i}$: Average effluent COD_{cr} concentration in the biochemical reaction tank on day i , mg/L. SG_i : sludge production at the wastewater treatment plant on day i , kg. P_v : Percentage content of organic matter in sludge on day i , %. ρ_s : Conversion factor between organic matter and COD_{cr} in sludge, with the value of 1.42 kg COD_{cr} /kg DS. EF_{CH_4} : CH_4 emission factor, kg CH_4 /kg COD_{cr} . B_0 : Methane yield coefficient for anaerobic COD_{cr} degradation, 0.25 kg CH_4 /kg COD_{cr} . MCF : CH_4 correction factor, 0.03. $m_{N_2O f2,i}$: N_2O emissions on day i , kg N_2O . $TN_{1,i}$: Average influent TN concentration in the biochemical tank on day i , mg/L. $TN_{2,i}$: Average effluent TN concentration in the biochemical tank on day i , mg/L. EF_{N_2O} : N_2O emission factor (default value: 0.016 kg N_2O -N/kg TN). C_{N_2O/N_2} : Molar mass ratio of N_2O to N_2 , 44/28. $m_{CO_2 f2,i}$: Fossil-derived CO_2 emissions from organic matter decomposition in aerobic tanks on day i , kg CO_2 .

The calculation of direct carbon emission intensity during the biological treatment phase is provided in Equations (13)–(15).

$$E_{CH_4 f2} = \frac{\sum_{i=1}^t m_{CH_4 f2,i} \times 28}{\sum_{i=1}^t Q_{1,i}} \quad (13)$$

$$E_{N_2O f2} = \frac{\sum_{i=1}^t m_{N_2O f2,i} \times 298}{\sum_{i=1}^t Q_{1,i}} \quad (14)$$

$$E_{CO_2 f2} = \frac{\sum_{i=1}^t m_{CO_2 f2,i}}{\sum_{i=1}^t Q_{1,i}} \quad (15)$$

$E_{CH_4 f2}$: Methane emission intensity from anaerobic digestion, kg CO_2 eq/m³. $E_{N_2O f2}$: Nitrous oxide emission intensity from the anoxic-aerobic phase, kg CO_2 eq/m³. $E_{CO_2 f2}$: Fossil-derived carbon emission intensity from organic matter decomposition in aerobic tanks, kg CO_2 /m³.

2.4.2. Indirect Carbon Emissions and Emission Intensity

Aeration constitutes the predominant factor contributing to indirect carbon emissions during the biological treatment phase. In fully aerated aerobic tanks, microorganisms sequentially decompose nitrogenous organic matter into NH_4^+ -N (ammonification), oxidize NH_4^+ -N to NO_2^- (nitrification), and ultimately convert NO_2^- to NO_3^- (nitration). Insufficient dissolved oxygen in aerobic tanks severely impedes nitration while promoting the generation of byproduct N_2O [29]. Concurrently, under aerobic conditions, phosphate-accumulating organisms (PAOs) regain metabolic activity, enabling them to assimilate phosphorus beyond growth requirements and ultimately remove it from wastewater as phosphate precipitates. Consequently, aeration in aerobic tanks demands substantial electrical energy, thereby inducing significant CO_2 emissions. Additionally, indirect carbon emissions arise from the electricity consumption for mixed liquor recirculation, mixing in biochemical tanks, and sludge return from secondary clarifiers and chemical reagents dosed in secondary clarifiers and disinfection. The calculation of indirect carbon emissions for this phase is provided in Equations (16)–(18).

$$m_{e3,i} = W_{3,i} \times EF_e \quad (16)$$

$$m_{p1,i} = m_{N,i} \times EF_{NaClO} \quad (17)$$

$$m_{p2,i} = m_{PAC,i} \times EF_{PAC} \quad (18)$$

$m_{e3,i}$: Carbon emissions from electricity consumption for aeration, internal recirculation, sludge return, mixed liquor mixing, and chemical dosing (phosphorus removal

agents/disinfectants) in the biological treatment phase on day i , kg CO₂eq. W_{3i} : Purchased electricity for the aforementioned processes in the biological treatment phase on day i , kW·h. $m_{p1,i}$: Indirect carbon emission equivalent from disinfectant dosing (NaClO) in disinfection units on day i kg CO₂eq. $m_{N,i}$: Disinfectant consumption on day i , kg. EF_{NaClO} : Carbon emission factor of sodium hypochlorite, 0.92 kg CO₂eq/kg [30]. $m_{p2,i}$: Indirect carbon emission from phosphorus removal agent dosing (PAC) in sedimentation tanks on day i , kg CO₂eq. $m_{PAC,i}$: Daily phosphorus removal agent consumption on day i , kg. EF_{PAC} : Carbon emission factor of polyaluminum chloride (PAC), 1.6 kg CO₂eq/kg [26].

The calculation of the corresponding indirect carbon emission intensity for the biological treatment phase is provided in Equations (19)–(21).

$$E_{e3} = \frac{\sum_{i=1}^t m_{e3,i}}{\sum_{i=1}^t Q_{1,i}} \quad (19)$$

$$E_{p1} = \frac{\sum_{i=1}^t m_{p1,i}}{\sum_{i=1}^t Q_{1,i}} \quad (20)$$

$$E_{p2} = \frac{\sum_{i=1}^t m_{p2,i}}{\sum_{i=1}^t Q_{1,i}} \quad (21)$$

E_{e3} : Carbon emission intensity from electricity consumption for aeration, internal recirculation, sludge return, mixed liquor mixing, and reagent of phosphorus precipitant/disinfectants in the biological treatment phase, kg CO₂eq/m³. E_{p1} : Indirect carbon emission intensity from disinfectant dosing in disinfection units, kg CO₂eq/m³. E_{p2} : Indirect carbon emission intensity from phosphorus removal agent dosing in sedimentation tanks, kg CO₂eq/m³.

2.5. Carbon Emission Calculation of Sludge Treatment Stage

Sludge treatment, as a critical process in municipal wastewater treatment systems, carries significant implications for life-cycle carbon emissions within wastewater treatment plant environments. This study systematically analyzes the carbon emission characteristics across various sludge treatment stages (as illustrated in Figure 1), elucidating their primary sources and formation mechanisms.

The residual sludge is generated in secondary clarifier.

Consequently, indirect carbon emissions during sludge treatment stage primarily originate from three sources: (1) Electricity consumption for sludge thickening, mixing, coagulant aid dosing, and filtering press operation; (2) Carbon emissions associated with chemical reagent (PAM) dosing; (3) Diesel combustion emissions during truck transportation of Dewatered sludge.

Waste Activated Sludge exhibits significant biphasic separation characteristics, with the liquid phase accounting for over 99% of the total volume. In engineering practice, a cascade dewatering process is typically employed for mass reduction: Primary mechanical thickening reduces moisture content to 97% (w/w). Polymeric flocculant (PAM) dosing precedes belt filter press treatment to enhance solid-liquid separation efficiency. Final belt filter press produces stabilized dewatered sludge with moisture content below 80% (w/w), which is subsequently transported to end disposal facilities via hermetically sealed skip loaders. The corresponding carbon emission calculations are provided in Equations (22)–(24).

$$m_{e6,i} = W_{6,i} \times EF_e \quad (22)$$

$$m_{CO_2f3,i} = m_{PAM,i} \times EF_{PAM} \quad (23)$$

$$m_{CO_2exp,i} = V_i \times \rho_{oil} \times EF_{oil} \quad (24)$$

$m_{e6,i}$: Indirect carbon emissions from electricity consumption during sludge treatment on day i , kg CO₂eq. $W_{6,i}$: Purchased electricity for sludge treatment processes on day i , kW·h. $m_{CO_2f3,i}$: Indirect CO₂ emissions from coagulant aid dosing during sludge dewatering on day i , kg CO₂eq. $m_{PAM,i}$: Mass of coagulant aid (PAM) dosed for sludge dewatering on day i , kg. EF_{PAM} : Carbon emission factor of PAM, 1.50 kg CO₂eq/kg [31]. $m_{CO_2exp,i}$: Indirect carbon emission equivalent from truck transport of dewatered sludge on day i , CO₂eq/kg. V_i : Diesel consumption for sludge transport trucks on day i , L, with a fuel consumption rate of 0.25 L/km·ton. ρ_{oil} : Density of diesel fuel, 0.86×10^3 kg/m³. EF_{oil} : Carbon emission factor for diesel combustion, 3.15 kg CO₂eq/kg [26].

The calculation of the corresponding indirect carbon emission intensity for the sludge treatment stage is provided in Equations (25)–(27).

$$E_{e6} = \frac{\sum_{i=1}^t m_{e6,i}}{\sum_{i=1}^t Q_{1,i}} \quad (25)$$

$$E_{CO_2f3} = \frac{\sum_{i=1}^t m_{CO_2f3,i}}{\sum_{i=1}^t Q_{1,i}} \quad (26)$$

$$E_{CO_2exp,i} = \frac{\sum_{i=1}^t m_{CO_2exp,i}}{\sum_{i=1}^t Q_{1,i}} \quad (27)$$

E_{e6} : Indirect CO₂ emission intensity from electricity consumption during sludge treatment, kg CO₂eq/m³. E_{CO_2f3} : Indirect CO₂ emission intensity from PAM in sludge dewatering, kg CO₂eq/m³. $E_{CO_2exp,i}$: Indirect CO₂ emission intensity from truck transport of dewatered sludge, kg CO₂eq/m³.

3. Results and Discussion

To quantify the total carbon emissions and carbon emission intensity of a wastewater treatment plant (employing the AAO process) in Hunan Province, operational log data for 2023 were obtained. However, as these logs only provided the plant's aggregate electricity consumption, they proved insufficient for granular carbon accounting across individual treatment units. To address this limitation, electricity allocation ratios for AAO process units were from the relevant literature [32], enabling approximation of electricity consumption per treatment stage. The electricity distribution profile across the plant's treatment units is illustrated in Figure 2.

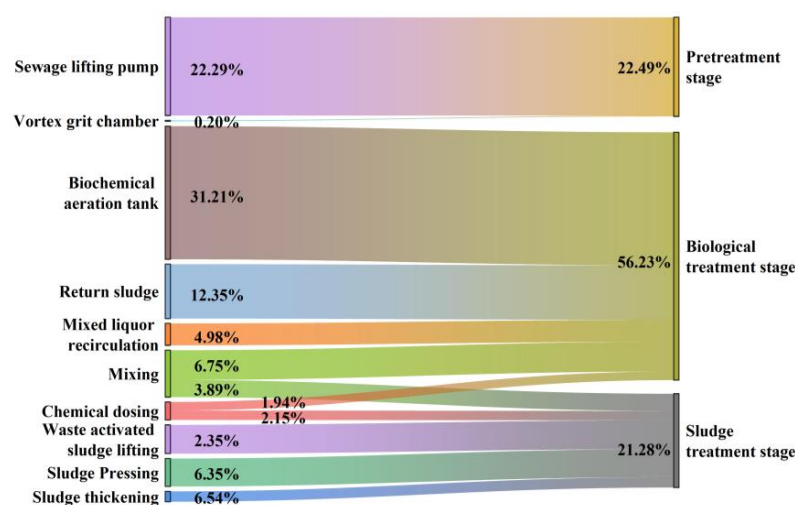


Figure 2. Composition of electricity consumption in each link of the AAO process in the wastewater treatment plant.

Figure 2 reveals that the biological treatment stage accounts for 56.23% of total electricity consumption, representing the most energy-intensive stage throughout the wastewater treatment process. This predominance is primarily attributed to aerobic aeration and sludge return, which collectively constitute 42.56% of the plant's total electricity demand. Concurrently, the preliminary treatment stage contributes 22.29% to overall consumption, largely driven by sewage pumping stations. Meanwhile, sludge treatment accounts for 21.28% of total electricity usage, with belt filter press operation exhibiting the highest energy intensity (6.54%) within this stage.

Given that certain carbon emission source denominations exhibit excessive length for graphical representation, abbreviations are adopted for all emission sources, as specified in Table 2.

Table 2. Names of carbon emission sources and their abbreviation for the three treatment stages, including the emissions and emission of each source.

Phase	Carbon Source	Abbreviation	Emission (kg/y)	Intensity (kg CO ₂ eq/m ³)
Pretreatment stage	Fossil-derived CO ₂	CO ₂ f ₁	13,780	0.00018
	Methane	CH ₄ f ₁	1389	0.00052
	Nitrous oxide	N ₂ O f ₁	1702	0.00676
	Sewage lifting pump	e ₁	2,255,517	0.03006
	Cyclone grit chamber	e ₂	20,238	0.00027
	Methane	CH ₄ f ₂	74,658	0.02786
	Nitrous oxide	N ₂ O f ₁	84,273	0.33275
Biological treatment stage	Fossil-derived CO ₂	CO ₂ f ₂	1,728,081	0.02303
	Aeration	e ₃	3,056,933	0.04074
	Internal recirculation	e ₄	503,923	0.00672
	sludge return	e ₅	1,249,690	0.01666
	Mixed liquor mixing	e ₆	683,029	0.00910
	Chemical reagent addition	e ₇	196,101	0.00261
	Disinfectants	p ₁	818,901	0.01091
	Phosphorus precipitant	p ₂	2,213,548	0.02950
	Sludge thickening	e ₈	237,759	0.00317
	Sludge dewatering via filter pressing	e ₉	642,553	0.00856
Sludge treatment stage	Flocculation aid dosing	e ₁₀	217,557	0.00290
	Conveyance of WAS	e ₁₁	661,779	0.00882
	Sludge agitation	e ₁₂	393,627	0.00525
	Coagulant aids	CO ₂ f ₃	13,545	0.00018
	Sludge transportation	CO ₂ exp	518,610	0.00691

3.1. Analysis of Accounting Results in the Pretreatment Stage

During the pretreatment stage, direct carbon emissions—specifically CO₂, N₂O, and CH₄ generated from municipal sewer networks—were incorporated into the accounting framework. This critical step is conventionally overlooked in traditional accounting methods, despite these emissions constituting a non-negligible share of the total carbon footprint. Quantitative results are presented in Figure 3 and Table 2.

As evidenced in Figure 3, carbon emission sources exhibit substantial variations. Table 3 summarizes the direct and indirect carbon emissions during the pretreatment stage. Analysis reveals that direct emissions amount to 17 t CO₂eq/y, while indirect emissions reach 2276 t CO₂eq/y, 135-times higher than direct emissions. This demonstrates that controlling indirect carbon emissions is critical for effective mitigation in the pretreatment stage.

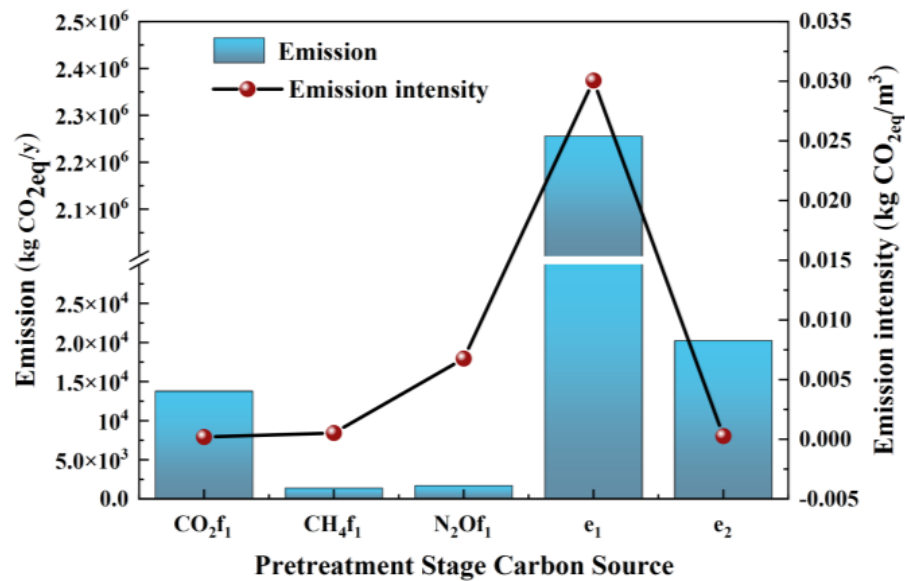


Figure 3. The emission and intensity of each carbon emission in the pretreatment stage.

Table 3. Carbon emission and emission intensity of the three treatment stages and the whole plant are divided into three major emission types and six emission sources.

Phase		Direct Emission			Electricity Emission	Chemical Emission		Total Emission
		CO ₂ -Fossil	CH ₄	N ₂ O	CO ₂ -Electricity	CO ₂ -Chemical	CO ₂ -Transportion	
Pretreatment stage	Emission (tCO _{2eq} /y)	14	35	507	2276	-	-	2832
	Intensity (kgCO _{2eq} /m ³)	0.00018	0.00052	0.00672	0.03033	-	-	0.03775
Biological treatment stage	Emission (tCO _{2eq} /y)	1728	1866	25,113	5690	3032	-	37,429
	Intensity (kgCO _{2eq} /m ³)	0.02303	0.02786	0.33275	0.07583	0.04041	-	0.49988
Sludge treatment stage	Emission (tCO _{2eq} /y)	-	-	-	2153	14	519	2686
	Intensity (kgCO _{2eq} /m ³)	-	-	-	0.0287	0.00018	0.00691	0.03579
Whole plant	Emission (tCO _{2eq} /y)	1742	1901	25,620	10,119	3046	519	42,947
	Intensity (kgCO _{2eq} /m ³)	0.02321	0.02838	0.33947	0.13486	0.04059	0.00691	0.57342

Seen from the perspective of emission, fossil-derived carbon emissions (CO₂f₁) in municipal sewer networks exhibit the lowest specific emission and are statistically negligible. Furthermore, both methane-equivalent emission intensity (CH₄f₁) in sewer networks and equivalent emission intensity of cyclone grit chambers (e₂) fall below 0.005 kg CO_{2eq}/m³, indicating they are non-priority sources for mitigation. Conversely, both nitrous oxide-equivalent emission intensity (N₂O f₁) and carbon emission intensity of lifting pump stations exceed 0.005 kg CO_{2eq}/m³, representing the critical targets for carbon reduction in pretreatment. Notably, pump station mitigation should enjoy priority, with the adoption of the following measures. Firstly, to enhance energy efficiency via high-efficiency equipment retrofitting, variable frequency drive (VFD) technology and hydraulic calculation optimization. Secondly, to adopt intelligent control systems such as IoT sensors for real-time monitoring of wet-well levels and pipe network flow, and AI-driven pump operation optimization algorithms.

3.2. Analysis of Accounting Results in the Biological Treatment Stage

The biological treatment stage is the core process in wastewater treatment, with its decisive role being unequivocal. This phase exhibits the highest levels of both direct

and indirect carbon emissions. Notably, the studied wastewater treatment plant (WWTP) deliberately abstains from methane (CH_4) recovery, instead, emits it directly to the atmosphere. Furthermore, no external carbon source was supplemented during the anoxic phase of biological treatment. The quantified carbon emissions for this stage are presented in Figure 4.

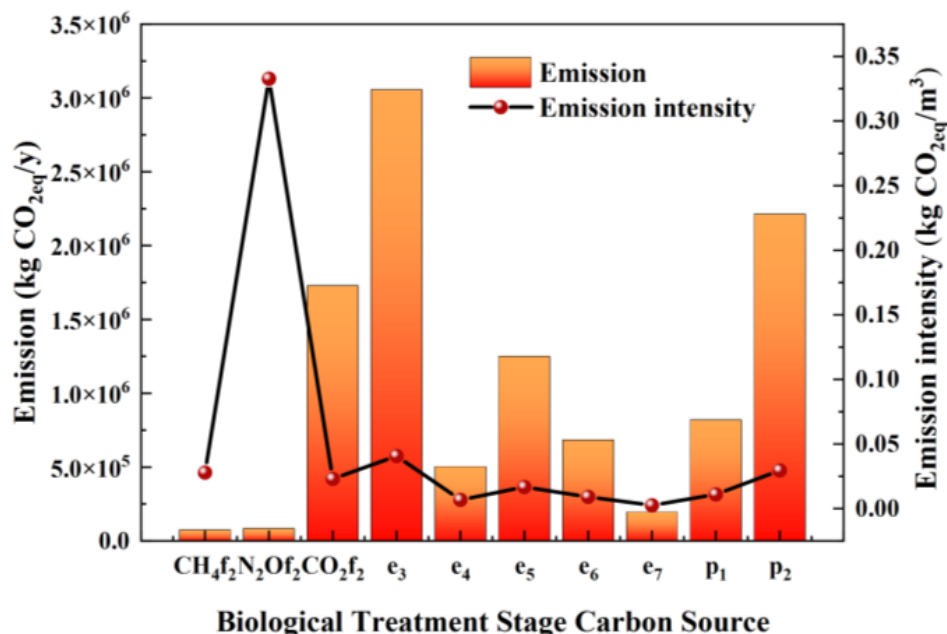


Figure 4. The emission and intensity of each carbon emission in the biological treatment stage.

Carbon emission sources in the biological treatment stage exhibit significant disparities (Figure 4). Aeration (e_3) dominates emissions at 3057 t CO_{2eq}/y, exceeding the second-largest source—phosphorus removal agents (p_2)—by 1.4-folds. Comparative analysis of Table 3 and Figure 2 confirms that aeration emissions surpass those from pretreatment and sludge treatment stages. Notably, aeration consumes 30.21% of the WWTP's total electricity, yet yields the lowest specific emissions from CH₄ release (74.7 t CH₄/y), constituting merely 2.44% of aeration-related emissions. Analysis by emission type (Table 2) reveals that direct emissions (1877 t CO₂/y) are eclipsed by indirect emissions (8721 t CO_{2eq}/y). Critically, CH₄ and N₂O emissions from biological treatment possess exceptionally high global warming potentials (GWPs), with N₂O's GWP of 298, driving its equivalent emission intensity to 0.333 kg CO_{2eq}/m³. This phenomenon may stem from incomplete denitrification due to the absence of external carbon supplementation in anoxic zones, leading to accumulation and release of nitrogenous intermediates [28]. Electricity consumption generates 5690 t CO_{2eq}/y at an intensity of 0.076 kg CO_{2eq}/m³, of which aeration accounts for 0.041 kg CO_{2eq}/m³, establishing it as the primary target for electrical carbon mitigation. Conversely, emissions from mixed liquor recirculation, waste sludge return, agitation, and chemical dosing all demonstrate intensities <0.02 kg CO_{2eq}/m³, rendering them non-priority mitigation sources. Chemical consumption contributes 3032 t CO_{2eq}/y (intensity: 0.04 kg CO_{2eq}/m³), while phosphorus removal agents specifically account for 2214 t CO_{2eq}/y (intensity: 0.030 kg CO₂/m³), representing the key focus for chemical-related emission reduction.

The biological treatment stage is pivotal for carbon emission reduction in wastewater treatment plants (WWTPs). Firstly, methane (CH₄) stands as one of the few recoverable energy sources within WWTPs. Its recovery and utilization serve as a carbon sink, offering a dual benefit: mitigating direct greenhouse gas emissions and offsetting indirect

carbon emissions from electricity consumption. Secondly, enhanced nitrogen removal constitutes a critical component of emission reduction. Techniques such as aerobic granular sludge [33], anaerobic ammonium oxidation (anammox) [34,35], algal–bacterial symbiosis systems [36,37], and coupled aerobic–anoxic nitrous decomposition [38–40] have demonstrated significant efficacy in nitrogen removal. Addressing the high energy consumption associated with the aeration stage involves a two-pronged approach. On one hand, measures like optimizing aeration control, enhancing aeration equipment efficiency, improving aeration systems, and strengthening routine management and maintenance can reduce electricity demand during aeration. On the other hand, installing solar photovoltaic panels on-site (e.g., over biochemical reactors or sedimentation tanks) can generate green energy to partially take the place of coal-based electricity, thereby achieving energy saving and emission reduction [41]. Regarding carbon reduction linked to phosphorus removal chemicals, intelligent chemical dosing systems should be introduced for precision control by adjusting dosage based on fluctuating flow and water quality parameters. Concurrently, selecting phosphorus removal agents with lower carbon emission coefficients through experimentation can achieve the desired emission reduction.

3.3. Analysis of Accounting Results in the Sludge Treatment Stage

During the operation of the AAO wastewater treatment process, a significant characteristic emerges: its biological treatment system generates a substantial volume of excess sludge. For the treatment of this sludge with high water content, the key step lies in achieving efficient dewatering and volume reduction. The primary methods currently employed to reduce sludge water content are sludge thickening (including mixing) and sludge pressure filtration. Both methods require electrical energy consumption. Furthermore, polyacrylamide (PAM) is typically dosed prior to belt filter press to enhance dewatering efficiency. The carbon emission accounting results for this stage are presented in Figure 5.

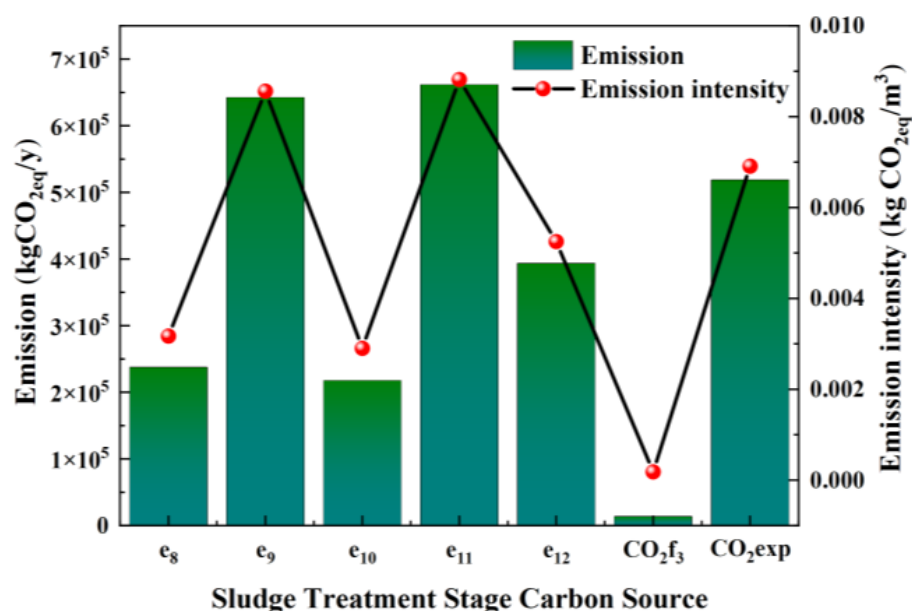


Figure 5. The emission and intensity of each carbon emission in the sludge treatment stage.

As shown in Figure 5, significant variations persist in the carbon emissions from different sources during this stage. Emissions from excess sludge lifting (e₁₁) were the highest at 662 t CO_{2eq}/y, while emissions from coagulant aids added during sludge thickening (CO_{2f3}) were the lowest at 14 t CO_{2eq}/y, representing a substantial disparity. Since anaerobic digestion of sludge was not implemented in this stage, direct emissions were not

considered. Emissions associated with sludge thickening (e_8), sludge pressure filtration (e_9), coagulant aid dosing (e_{10}), and mixing during sludge thickening (e_{12}) stemmed from electricity consumption, totaling 1491 t CO₂eq/y. Additionally, emissions from sludge transportation (CO_{2exp}) amounted to 519 t CO₂eq/y.

Regarding carbon emission intensity, the lifting of excess sludge exhibited the highest intensity at 0.0088 kg CO₂eq/m³. Sludge pressure filtration ranked second with an emission intensity of 0.0086 kg CO₂eq/m³, followed by sludge transportation at 0.0069 kg CO₂eq/m³. The emission intensities of all other carbon sources were below 0.005 kg CO₂eq/m³. Considering both the total carbon emissions and emission intensities during the sludge treatment stage, carbon mitigation efforts should primarily focus on reducing electrical energy consumption. This can be achieved by implementing real-time monitoring of energy usage in sludge treatment equipment and utilizing data analysis to identify high-energy-consumption equipment and processes for optimization. Additionally, strategies such as energy substitution, sludge resource recovery and carbon sequestration technologies, and the synergistic application of policy and market mechanisms can be employed to further reduce carbon emissions.

3.4. Analysis of Whole Plant Accounting Results

The above is an analysis of carbon emissions across different treatment stages within the wastewater treatment plant, with specific carbon reduction recommendations proposed for each stage. To gain a comprehensive understanding of the plant's carbon footprint, it is imperative to consider both the total carbon emissions and the emission intensity. The corresponding data are presented in Figure 6 and Table 3.

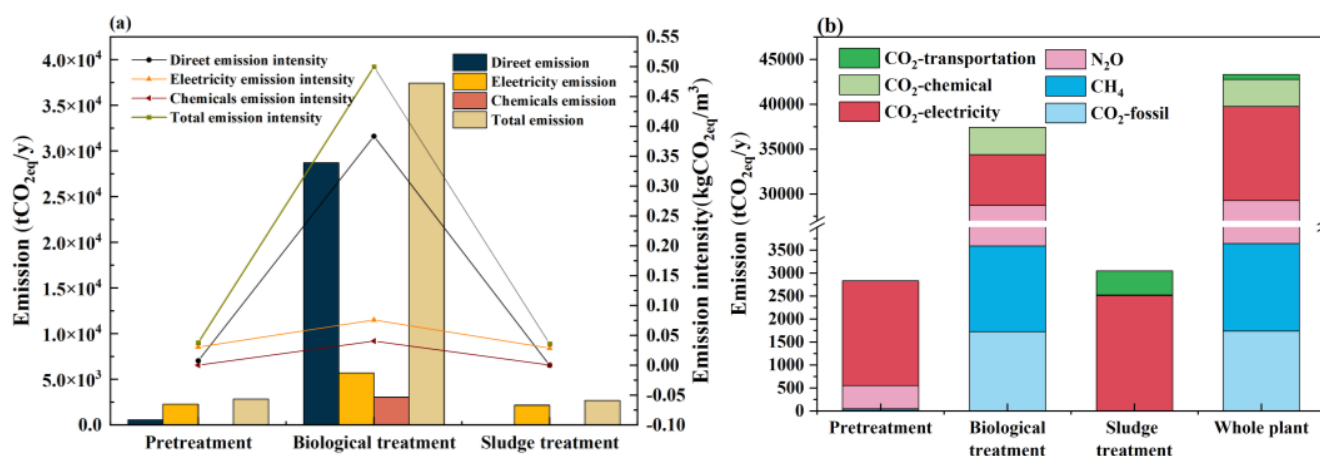


Figure 6. The different carbon emissions and emission intensities at each stage. (a) Direct, electricity, chemical, and total emissions, and emission intensities, of different stages. (b) Different types of carbon emissions at different stages.

Data presented in Table 3 and Figure 6a indicate that the studied WWTP exhibits an annual carbon footprint of 42,947 t CO₂eq/y with an emission intensity of 0.573 kg CO₂/m³. This carbon intensity is notably lower than the reported value of 1.002 kg CO₂/m³ in Li et al.'s study [5], which could be partially attributed to significantly higher influent concentrations of BOD, COD, TN, and TP at the WWTPs investigated in their research. Direct emissions account for 29,263 t CO₂eq/y, while indirect emissions total 13,684 t CO₂eq/y. Direct emissions constitute the dominant portion, representing 68.14% of the plant's total carbon footprint. This distribution pattern aligns closely with Yu et al.'s findings (70% reported) [42], confirming that direct emissions dominate the carbon profile in wastewater treatment operations. Regarding indirect emissions, the preliminary treatment

stage contributes 2276 t CO₂eq/y, and the sludge treatment stage emits 2686 t CO₂eq/y, both stages being comparable in magnitude. In contrast, the biological treatment stage generates 8722 t CO₂eq/y (accounting for 63.74% of the total indirect carbon emissions at the wastewater treatment plant), which is 3.8 times and 3.2 times the emissions of the preliminary and sludge treatment stages, respectively. Thus, the biological treatment stage represents the primary source of indirect emissions. While direct emissions dominate the plant's overall carbon footprint, the three treatment stages exhibit distinct emission profiles. The preliminary treatment stage emits 556 t CO₂eq/y in direct emissions, whereas the biological treatment stage contributes 28,707 t CO₂eq/y. Direct emissions were not considered for the sludge treatment stage. Notably, the biological treatment stage accounts for the majority of direct emissions within the plant.

The examination of the overall carbon emission intensity of the wastewater treatment plant reveals that the indirect emission intensity for the entire plant is 0.182 kg CO₂eq/m³, while the direct emission intensity is 0.391 kg CO₂eq/m³. This clearly indicates that reducing direct emissions is the primary focus for carbon mitigation across the plant. Within the biological treatment stage, the indirect emission intensity reaches 0.116 kg CO₂eq/m³, which is 1.76 times the combined indirect emission intensity of the preliminary and sludge treatment stages. This significant disparity is primarily attributed to the high electricity consumption and substantial chemical dosage requirements within the biological treatment process. Consequently, future municipal wastewater treatment plants face heightened demands, necessitating the urgent development of more precise aeration and chemical dosing control systems. Regarding direct emissions, the biological treatment stage exhibits an intensity of 0.384 kg CO₂eq/m³, which is 51.8 times greater than the direct emission intensity of the preliminary treatment system (0.007 kg CO₂eq/m³). Notably, within the biological treatment stage, the emission intensity of nitrous oxide (N₂O) alone is particularly high, at 0.333 kg CO₂eq/m³. Undoubtedly, the biological treatment stage occupies a central position in the carbon reduction strategy for wastewater treatment plants, both in terms of absolute emission quantity and emission intensity. Therefore, adopting novel nitrogen removal processes—such as Partial Nitrification-Denitrification (PND) and Anaerobic Ammonium Oxidation (anammox)—in biological treatment systems enables substantial mitigation of operational carbon emissions in wastewater treatment plants.

As shown in Table 3 and Figure 6b, the distribution of different carbon emission sources varies across the three treatment stages of the wastewater treatment plant. The preliminary treatment stage comprises four emission sources, among which CO₂ emissions from electricity consumption are the highest, accounting for 80.4%. The biological treatment stage encompasses five emission sources. With the exception of sludge transportation, emissions from all the other sources represent the highest levels among the three stages. Notably, equivalent emissions of N₂O are particularly dominant, constituting 67.1% of the stage's total emissions. The sludge treatment stage includes three emission sources, with CO₂ emissions from electricity consumption again being the predominant contributor at 80.2%. Therefore, from the perspective of emission source types, CO₂ emissions arising from electricity consumption and N₂O emissions from biochemical reactors must be prioritized as key targets for future carbon reduction in wastewater treatment plants.

4. Conclusions

Employing a life-cycle carbon footprint accounting methodology, this study systematically investigates the carbon emission profiles and mitigation potential across treatment units in an urban wastewater treatment plant (WWTP) located in Hunan Province, China. The principal findings are as follows:

- (1) The plant's total annual carbon emissions are 42,947 t CO₂eq, with an emission intensity of 0.573 kg CO₂eq/m³. Direct emissions account for 29,263 t CO₂eq, while indirect emissions total 13,684 tCO₂eq. Direct emissions constitute the dominant portion, representing 68.14% of the plant's overall carbon footprint.
- (2) The biological treatment stage constitutes the core carbon emission hotspot, with direct emissions (CH₄, N₂O, CO₂) and indirect emissions (electricity, chemicals, transportation) accounting for 68.14% and 63.74% of the plant's total emissions, respectively. Notably, N₂O emerges as the primary contributor to direct emissions due to its high global warming potential (GWP), exhibiting an emission intensity of 0.333 kg CO₂eq/m³. In contrast, both preliminary and sludge treatment stages are dominated by indirect emissions from electricity consumption.
- (3) To achieve energy conservation and emission reduction, the biological treatment stage requires optimization of the aeration system through intelligent control technologies to reduce air supply, alongside methane (CH₄) recovery for carbon offsetting and adoption of innovative nitrogen removal processes. For the preliminary treatment stage, variable frequency drives (VFDs) and IoT technologies should be implemented to enhance pumping station efficiency. In the sludge treatment stage, there should be many critical pathways for carbon mitigation, such as low-carbon dewatering technologies, energy substitution strategies, sludge resource recovery and carbon sequestration techniques, and synergistic policy-market mechanisms.

This study shows that the integration of sewer network emissions and process-level carbon intensity provides a more granular framework than existing IPCC-based approaches, enabling targeted mitigation.

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Data Availability Statement: The data generated in this study are available upon request from the corresponding author.

Conflicts of Interest: Author Saijun Zhou was employed by the company Hunan University of Science and Technology Engineering Testing Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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