C. Wang et al. (Eds.)

doi:10.3233/ATDE230347

Carbon Footprint Analysis and Its Optimization Prediction of China's Municipal Sewage Treatment Industry

Wenrui XU[a,b] and Hongliang DAI[b,1]
[a] *School of Marxism, Hohai University, Nanjing 210098, Jiangsu, China*
[b] *School of Environmental and Chemical Engineering, Jiangsu University of Science and Technology, Zhenjiang 212003, Jiangsu, China*

Abstract. Sewage treatment is an efficient approach to achieving water resource recycling and safeguarding the environment. The municipal sewage treatment plants must not only meet discharge standards, but also incorporate energy-saving and carbon reduction measures during the sewage treatment process under China's "dual carbon" strategy. This study calculated and analyzed carbon emissions from China's municipal sewage treatment industry between 2012 and 2021, and forecasted the carbon emission intensity and amount in 2030. The findings revealed that the total carbon emissions increased from 29.33 Mt CO_2e to 58.95 Mt CO_2e over a decade, with direct and indirect emissions rising by 78.04% and 143%, respectively. Direct and indirect emissions in 2021 comprised 57.37% and 42.63% of the industry's total carbon emissions, respectively. Sewage treatment plants accounted for the largest unit of carbon emissions, representing an average of 35%. Without effective carbon reduction measures, the industry's carbon emissions are projected to reach 67.21 Mt CO_2e in 2030. Implementing two optimization schemes, the total carbon emissions in 2030 are anticipated to decline to 65.21 Mt CO_2e (Optimized 1) or 62.19 Mt CO_2e (Optimized 2), corresponding to a 2.98% or 7.46% reduction, respectively, showing a turning point of carbon peaking. These results can provide theoretical and data support for carbon neutralization planning in the sewage treatment industry, and are essential in achieving carbon reduction goals and addressing global warming.

Keywords. Carbon footprint analysis, sewage treatment plant, carbon emissions reduction, carbon peaking

1. Introduction

In the face of the increasingly severe environmental problem of global warming, controlling global carbon emissions and achieving carbon neutrality are important ways and measures to solve the above problem. The signing of the Paris Agreement in 2015 marked the formation of a unified front for global action on climate change [1]. In 2020, China established explicit targets for achieving a carbon peak by 2030 and carbon neutrality by 2060. The primary objective of the "dual-carbon" strategy is to advocate for green, environmentally friendly, and low-carbon production and lifestyle, promote and guide innovation in green technology, improve people's living standards, and enhance the quality of the ecological environment. To achieve the "dual-carbon"

[1] Corresponding Author, Hongliang DAI, School of Environmental and Chemical Engineering, Jiangsu University of Science and Technology, Zhenjiang 212003, Jiangsu, China; Email: daihongliang@just.edu.cn.

strategy objectives, industries have begun to focus on their carbon emissions and make carbon neutrality a goal for industry development [2].

Wastewater treatment is an important barrier to achieving water resource recycling and protecting the ecological environment, but it is also a high-energy-consuming industry. It is predicted that carbon emissions from China's municipal sewage industry will account for 2.95% of the national carbon emissions in 2030 [3]. Although wastewater treatment achieves the transformation and removal of pollutants, obtains good effluent, and makes contributions to improving the water ecological environment, it consumes a large amount of energy and resources during the treatment process, and emits a large amount of greenhouse gases and solid waste such as sludge. Therefore, conducting a systematic statistical analysis of carbon emissions in wastewater in recent years is of great significance for solving the industry's high energy consumption problem and achieving dual-carbon goals [4].

One of the major greenhouse gases produced in large quantities during sewage treatment is CH_4. CH_4 is mainly generated under anaerobic conditions, thus it is emitted during sewage collection and treatment processes as well as sludge treatment and disposal processes [5]. Another greenhouse gas, N_2O, is mainly produced during the biochemical process and emitted in the aeration zone. It is generally believed that N_2O is formed through three pathways, namely, hydroxylamine oxidation, heterotrophic denitrification, and nitrification-denitrification [6]. The selection of carbon emission accounting models largely determines the reliability of greenhouse gas emissions [7]. Currently, the widely used accounting models include the emission factor method and measurement-based method. The emission factor method was first proposed by the Intergovernmental Panel on Climate Change (IPCC) to calculate carbon emissions by determining emission sources, constructing activity data and emission factors, and multiplying activity data and emission factors [8]. The measurement-based method measures greenhouse gas emissions from emission sources on site, and summarizes the data to obtain carbon emissions. However, this method has fewer intermediate links and accurate results, but obtaining the data is relatively difficult. Since the Ministry of Housing and Urban-Rural Development of China (MOHURD-PRC) has provided public data on sewage volume and grid emission factors, this article uses the emission factor method to calculate and analyze the carbon emissions of China's municipal sewage treatment industry.

This article calculates and analyzes the carbon emissions of China's municipal wastewater treatment industry from 2012 to 2021, and then predicts the optimization of carbon emission intensity and carbon emissions of China's municipal wastewater in 2030 using two optimization methods: the addition of heat pumps and the use of high-efficiency activated sludge. The research results comprehensively reveal the spatial distribution characteristics and spatiotemporal changes of carbon emissions in China's urban wastewater industry, which is of great significance for mastering China's carbon emissions data, formulating relevant emission reduction policies, and planning for the future development of this industry.

2. Materials and Methods

2.1. Scope of Carbon Emissions Accounting

This study calculates the emissions of the three main greenhouse gases (CH_4, N_2O, and

CO_2 from fossil fuels) in wastewater treatment based on data provided by the MOHURD-PRC. The study analyzes the carbon emissions of China's wastewater treatment industry over the decade from 2012 to 2021 [9]. Due to the fact that a unit of CH_4 and N_2O can absorb more heat in the atmosphere compared to a unit of CO_2, different greenhouse gases are converted into carbon dioxide equivalents (CO_2e) for comparison. According to the IPCC, one ton of CH_4 and one ton of N_2O are equivalent to 25 tons and 298 tons of CO_2, respectively [10].

The scope of greenhouse gas accounting for the study is shown in Figure 1, including five emission units: sewer system, wastewater treatment plants (WWTPs), sludge disposal, effluent, and untreated sewage. All five units generate direct emissions, while the sewer system, WWTPs, and sludge disposal units also generate indirect emissions.

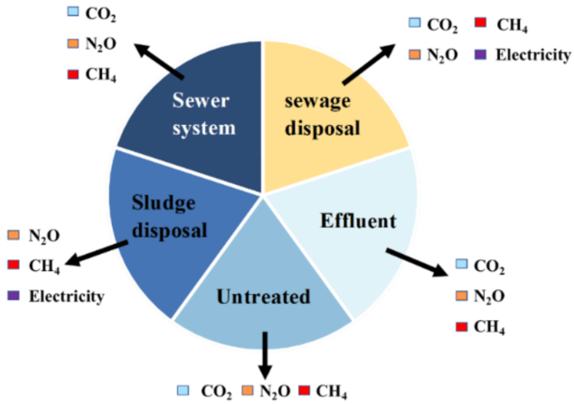


Figure 1. Accounting units of greenhouse gas emissions.

2.2. Determination of Carbon Emission Factors

2.2.1. Benchmark Emission Factors for China's Regional Power Grid

The benchmark emission factors for China's regional power grid published by the Ministry of Ecology and Environment of China (MEE-PRC) were used in this study to calculate the indirect emissions caused by electricity consumption. As specific data for each region were not officially released for the years 2020 and 2021, the national average carbon emission factor for the power grid was used instead [11].

2.2.2. Determining Emission Factors for Other Units

The sewer system is composed of pipes and related construction that collects and transports urban wastewater, and its network system is a potential source of CH_4 and N_2O greenhouse gas emissions. The sewer system can be divided into two types according to the power source: rising sewer pipes and gravity sewer pipes. The different operating modes result in different anaerobic environments, leading to different carbon emission intensities. The CH_4 emission intensity of rising pipes is greater than that of gravity pipes. Due to the anaerobic environment in the rising sewer pipes and a lack of research on N_2O emissions from rising pipes, the N_2O emissions from rising pipes are assumed to be 0 in this study [12]. The EF^{CH_4} of gravity pipelines is 0.83 g CH_4/m^3 and the EF^{N2O} is 0.0002 kg N_2O/kg TN_{inf} [13]. The lower the liquid level of gravity pipes, the greater the N_2O emission intensity [14, 15].

The treatment process of wastewater treatment plants exerts a considerable impact on the carbon emission intensity, making the emission factors for these plants more complex. Based on research on greenhouse gas emissions both domestically and internationally, emission factors for different treatment processes in sewage treatment plants have been obtained. The sequencing batch reactor (SBR) process has a higher N_2O emission factor than other processes, and the CH_4 and N_2O emission factors of the conventional activated sludge (CAS) process are both relatively high. It is important to note that even for the same treatment process; there is a large variation in greenhouse gas emission intensity.

There is limited research on greenhouse gas emissions from sludge disposal. Firstly, it is assumed that the carbon emissions from improperly dumped sludge are the same as those from sludge drying ponds. Since there is a lack of measured emission factor data for other sludge disposal processes, this article adopts the default values relevant studies for calculation [16].

The nitrifying bacteria in the sewage treatment plant will be discharged into the river with the effluent, causing the river to exhibit high N_2O emissions and higher carbon emissions compared to unpolluted water [17]. This makes the effluent a source of greenhouse gas emissions. Due to the lack of measured data on CH_4 emissions in the effluent, this study used IPCC default values [10]. This study assumes that the fossil source CO_2 emissions in the effluent are the same as those in the sewage treatment plant. Untreated wastewater is widely present in open sewers, pits, toilets, or marshes. Due to its high pollutant concentration, it forms an anoxic environment and has a greater potential for greenhouse gas emissions. In this study, the emission intensity of polluted water bodies was used as the emission factor for untreated wastewater calculation [18].

2.3. Optimization and Prediction of Carbon Emission Intensity and Carbon Emission

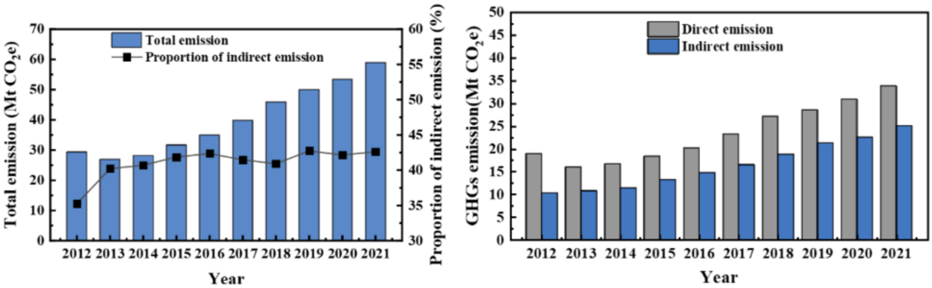
Two optimization schemes were proposed for predicting the future national carbon emission intensity and carbon emissions of wastewater treatment. The first optimization scheme involves the transformation of the existing activated sludge process by incorporating heat pumps and other methods for recovering thermal energy from secondary effluent. A sewage source heat pump is a variant of a water source heat pump that harnesses low-grade thermal energy resources generated from shallow groundwater, rivers, and lakes that have absorbed solar and geothermal energy on the earth's surface. This technology uses the heat pump principle to transfer low-grade thermal to high-grade thermal energy with minimal high-grade electrical energy input. The sewage source heat pump regards sewage as a low-temperature waste heat source and implements heat recovery from secondary effluent by directly setting up the heat pump in the sewage tank and using either the direct method of cooling and vaporization or the indirect method of absorbing heat from sewage using a heat exchanger in the heat source loop.

The second optimization scheme is to choose efficiently activated sludge, high-solids anaerobic digestion, and partial nitration/anaerobic ammonium oxidation. The primary principle of this process is to harness the substantial chemical energy present in wastewater for biogas production, which renders it more energy-efficient than conventional activated sludge methods for nitrogen removal [19]. Studies have shown that this scheme can increase the methane content of anaerobic digestion and overcome the instability of mainstream nitration/anaerobic ammonium oxidation operations [20].

3. Results and Discussion

3.1. Direct and Indirect Carbon Emissions in Municipal Wastewater Industry

The total carbon emissions from municipal wastewater from 2012 to 2021 are shown in Figure 2. The overall carbon emissions slightly increased (Figure 2a), from 29.33 Mt CO_2e in 2012 to 58.95 Mt CO_2e in 2021. Both direct and indirect emissions increased annually, with a growth rate of 78.04% and 143% over the 10 years, respectively (Figure 2b). In addition, the proportion of indirect emissions in total carbon emissions increased, from 35.24% in 2012 to 42.63% in 2019. In 2021, the total carbon emissions from municipal wastewater were 58.95 Mt, of which the direct emissions of greenhouse gases were 33.81 Mt CO_2e, accounting for 57.37% of the total emissions; the indirect emissions of greenhouse gases were 25.13 Mt CO_2e, accounting for 42.63% of the total emissions.



(a) (b)

Figure 2. The total emissions, direct emissions, and indirect emissions from the municipal sewage industry in the past decade in China.

3.2. Emissions from Each Unit in Municipal Sewage Industry

According to the analysis of carbon emissions by each unit (Figure 3a), the data indicates that the sewage treatment plant exhibits the highest proportion of carbon emissions among all units, with a mean percentage of 35%, and the emissions have increased from 8.57 Mt CO_2e in 2012 to 21.28 Mt CO_2e in 2021. The carbon emissions of the untreated unit gradually decreased over the decade, from 9.63 Mt CO_2e in 2012 to 2.78 Mt CO_2e in 2021, thanks to the improvement of sewage treatment facilities in recent years, which has increased the efficiency of sewage treatment and greatly reduced the untreated sewage volume. The carbon emissions of all remaining units have increased to a certain extent, with the carbon emissions of the sewage pipeline network system showing a more obvious increasing trend, from 4.6 Mt CO_2e in 2012 to 14.19 Mt CO_2e in 2021, with a growth rate of 308%. The proportion of carbon emissions from the effluent unit in the total carbon emissions is the smallest, with an average ratio of only 6.7%.

CH_4, N_2O, and electricity consumption units are the main components of total carbon emissions, so the emissions of the three gases were analyzed and calculated (Figure 3b). As shown in the figure, CH_4 was the largest greenhouse gas emission source in the early years, and increased year by year over the decade, from 13.55 Mt CO_2e in 2012 to 25.47 Mt CO_2e in 2021, with a growth rate of 87%. The overall trend of N_2O demonstrated an upward trajectory with an approximate growth rate of 82%. The greenhouse gas emissions from electricity consumption units increased from 9.79 Mt CO_2e in 2012 to 21.69 Mt CO_2e in 2021, with a growth rate of 221%. The increase in electricity consumption units was mainly due to the increase in the number of wastewater treatment facilities and the increase in wastewater volume, which was a drawback of higher wastewater treatment rates and better effluent quality.

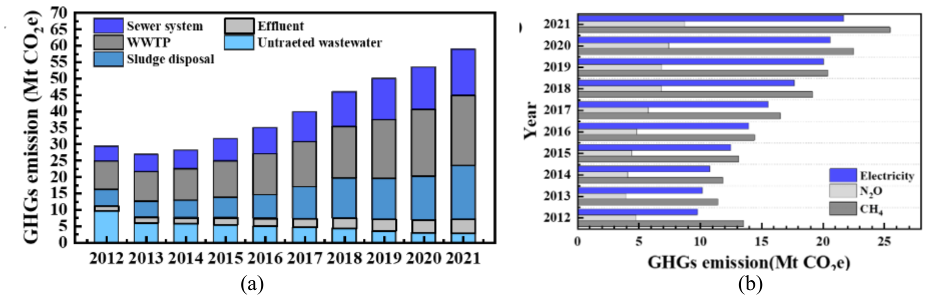


Figure 3. Carbon emissions and typical greenhouse gas emissions of each unit in the municipal sewage industry.

The dominant contributors to carbon emissions in the sewage network unit are CH_4 greenhouse gas emissions and electricity consumption (Figure 4a). The proportion of indirect emissions generated by electricity consumption is the largest, accounting for 51.7% of the total carbon emissions, while the proportion of N_2O emissions is only 2.5%. All three types of carbon emissions are increasing year by year, and CH_4 gas is increasing at the fastest rate, with a growth rate of 300% over the decade. This may be due to the increasing proportion of rising sewage pipelines in the sewage network system, which are gradually replacing gravity sewage pipelines and increasing the release of CH_4 gas. In 2021, the carbon emissions from CH_4 gas in the sewage network were 10.32 Mt CO_2e, N_2O gas emissions were 0.57 Mt CO_2e, and the carbon emissions from electricity dissipation were 3.69 Mt CO_2e.

The dominant contributors to carbon emissions from the sewage disposal unit are indirect emissions caused by electricity dissipation, N_2O gas emissions, and chemical consumption (Figure 4b). The growth rate of N_2O gas emissions in this unit is the highest, reaching 174%. The main reason for the growth is the gradual increase in sewage treatment volume and changes in related emission factor coefficients. Over the ten years, the carbon emissions from electricity dissipation in the sewage treatment plant unit increased from 4.82 Mt CO_2e to 11.62 Mt CO_2e. The proportions of CH_4 and CO_2 emissions from fossil sources in this unit are not high, and their growth rates are not significant.

The dominant contributors to carbon emissions in the sludge disposal unit are the gas emissions of CH_4 and N_2O (Figure 4c), which are mainly caused by the methods used for sludge treatment, such as sanitary landfill, incineration, and land use. Although the methods for sludge disposal are constantly improving, the increasing amount of wastewater treatment still leads to a year-on-year increase in carbon emissions from this unit. The growth rates of CH_4 and N_2O are 165% and 167%, respectively.

The dominant contributors to carbon emissions in the untreated effluent unit are significantly decreasing year by year, which is divergent from the pattern of carbon emissions in other units (Figure 4d). Methane gas (CH_4) has shown the most obvious decrease, with a reduction rate of 58.48%, from 5.01 Mt CO_2e in 2012 to 2.08 Mt CO_2e in 2021. This is mainly due to the improvement of sewage treatment facilities in recent years, which has led to a notable reduction in untreated sewage volume, and an increase in the sewage treatment rate.

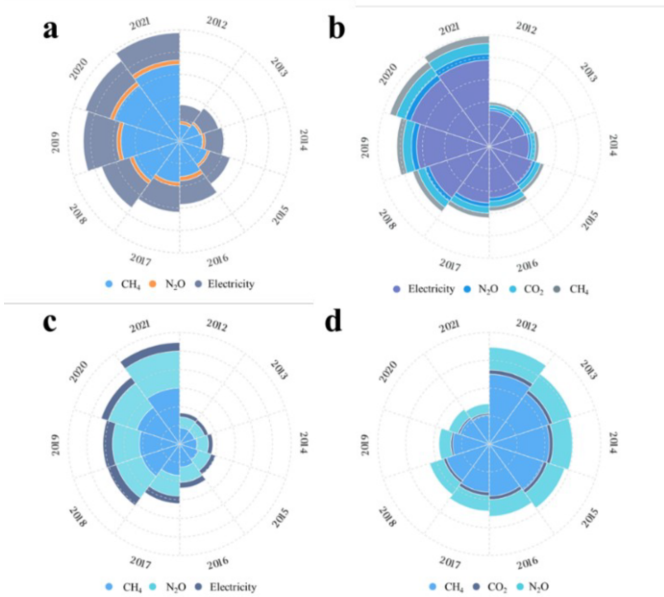


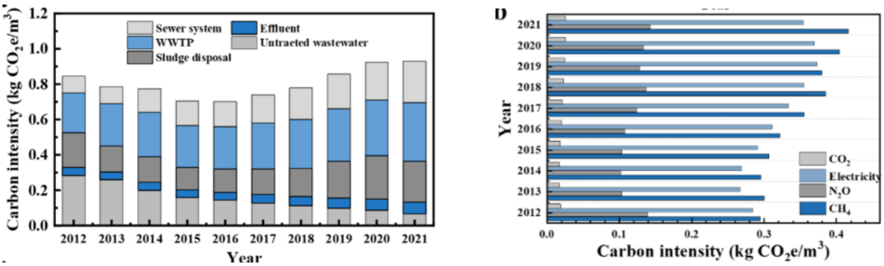
Figure 4. Trend of carbon emissions from sewage network, sludge treatment plant, sludge disposal, and untreated effluent.

3.3. Analysis of Carbon Emission Intensity in Municipal Wastewater Industry

The carbon emission intensity denotes the quantity of greenhouse gas emissions produced per unit of wastewater treated. As shown in Figure 5a, the carbon emission intensities of different units have been reduced to some extent in the first few years, with a decrease of 0.14 kg CO_2e/m^3 from 2012 to 2015, but have slightly increased in the later years. This phenomenon indicates that the processes and management methods used in wastewater treatment cannot further improve the carbon emission intensity after a certain degree of improvement with social development. At the same time, the increase in population density and social activities has caused an increase in carbon emissions in the wastewater treatment industry, resulting in an increase in emission intensity. The carbon emission intensity is the highest in the wastewater treatment and sludge disposal units, while the carbon emission intensity of untreated wastewater has decreased year by year, from 0.28 kg CO_2e/m^3 in 2012 to 0.06 kg CO_2e/m^3 in 2021, a decrease of approximately 78%.

Figure 5b shows the carbon emission intensity of different greenhouse gas sources.

By classifying into direct and indirect emissions, it can be seen clearly that the carbon emission intensity of direct emissions has decreased, and the carbon emission intensity of the electricity consumption unit in the indirect emissions has increased, from 0.28 kg CO_2e/m^3 in 2012 to 0.35 kg CO_2e/m^3 in 2021, an increase of about 25%. The reason for this phenomenon is the increase in the electricity consumption of wastewater treatment per unit of wastewater due to the higher wastewater discharge standards in recent years. The carbon emission intensity of direct emissions is mainly represented by CH_4 gas, which has decreased from 0.29 kg CO_2e/m^3 in 2012 to 0.41 kg CO_2e/m^3 in 2021, while the carbon emissions of fossil sources, which also belong to direct emissions, have not changed significantly.



(a) (b)

Figure 5. Carbon emission intensity of each treatment unit and emission pathway.

3.4. Prediction of Carbon Emissions and Carbon Emission Intensity of Municipal Wastewater Industry

The treatment process units are identified as the primary sources of carbon emissions in sewage treatment plants. It is necessary to optimize the process to improve energy and resource recovery efficiency. "Optimized 1" refers to a modified version of the activated sludge process. which recovers thermal energy through the addition of a heat pump for secondary effluent. According to relevant studies [21], the average thermal recovery rate in the effluent is about 1.18 kWh/m^3. Assuming a 1.8%/year upgrade rate for this strategy from 2012, the carbon emission intensity will decrease to 0.84 kg CO_2e/m^3 by 2030 (Figure 6a). "Optimized 2" involves the implementation of high-efficiency activated sludge technology and high-solids anaerobic digestion of sludge, and partial nitrification/anoxic ammonia oxidation process. Assuming a 5%/year upgrade rate for this strategy from 2012, the carbon emission intensity will decrease to 0.80 kg CO_2e/m^3 by 2030.

Through the above two optimization schemes, it is calculated that by 2030, the total carbon emissions of China's sewage treatment industry will reach 65.21 Mt CO_2e (Optimized 1) or 62.19 Mt CO_2e (Optimized 2). Compared with the predicted situation without optimization, they will decrease by 2.98% or 7.46%, respectively (Figure 6b). According to the construction goals of the 13th Five-Year Plan and the requirement to shift from "sewage treatment" to "recycling and reuse," it is expected that the sewage treatment rate and reuse rate will greatly increase by 2030, and the treatment rate and sludge disposal rate will approach 100%. The scale and technological structure of China's power industry will also undergo huge changes, with non-fossil energy generation accounting for 60% of the total electricity generation, and the grid emission coefficient will be reduced to 0.46-0.48 kg CO_2/kWh.

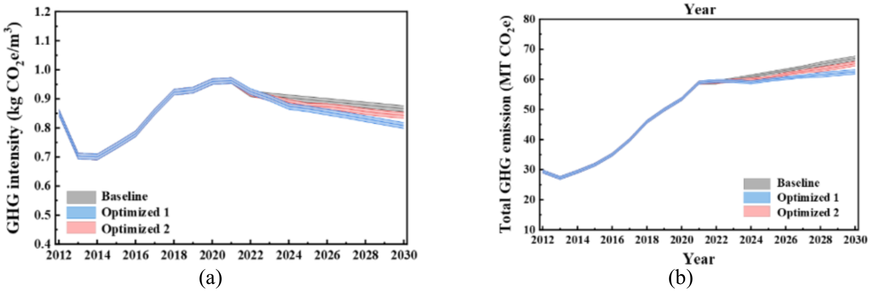


Figure 6. Prediction of carbon emission intensity and carbon emissions in the national sewage treatment industry.

According to the above predictions, if China is to achieve its national "carbon peak and carbon neutrality" plan, the main focus of carbon emission control in municipal sewage treatment in the future should be the carbon emission regulation of sewage treatment units, as it accounts for the largest proportion of carbon emissions. At the same time, attention should also be given to the sludge unit and sewage pipe network, including preventing the escape of greenhouse gases in the sewage pipe network and harmless treatment of sludge. Measures to be adopted include but are not limited to: renovating existing activated sludge processes, recovering heat energy from secondary effluent through the use of heat pumps, and selecting efficiently activated sludge, high solids retention anaerobic digestion, and partial nitrification/anoxic ammonia oxidation processes.

4. Conclusions

This article presents a statistical analysis of carbon emissions from China's municipal sewage treatment industry over the past ten years, from 2012 to 2021, and predicts carbon emission intensity and total emissions for 2030. The carbon emissions from China's municipal sewage treatment industry increased gradually from 2012 to 2021, reaching 58.95 Mt CO_2e in 2021. The carbon emissions from sewage treatment plants accounted for the largest proportion, at 35%. When classified by greenhouse gas emissions, energy consumption units were the largest source of carbon emissions. By prediction, China's sewage treatment industry's carbon emissions will reach 67.21 Mt CO_2e in 2030, with a carbon emission intensity of 0.86 kg CO_2e/m^3. Using two optimization scenarios, the total carbon emissions in 2030 are expected to decrease by approximately 2.98% or 7.46%. The research findings indicate that the main direction of future carbon emissions reduction in the municipal sewage industry should focus on sewage treatment plant units, with a particular emphasis on optimizing energy consumption units.

Acknowledgments

This study was funded by the National Natural Science Foundation of China (No. 51908252), the Postdoctoral Research Foundation of China (No. 2019M652274), and the Jiangsu Province Industry-University-Research Cooperation Project (No. BY2021420).

References

[1] Rollo AM, Rollo A, Mora C. The tree-lined path to carbon neutrality. Nat. Rev. Earth Environ. 2020; 332:1-1.
[2] Chen J, Luo Y, Sinsabaugh RL. Subsoil carbon loss. Nat. Geosci. 2023;16:284-285.
[3] Du W, Lu J, Hu Y, Xiao J, Yang C, Wu J, Huang B, Cui S, Wang Y, Li W. Spatiotemporal pattern of greenhouse gas emissions in China's wastewater sector and pathways towards carbon neutrality. Nat. Water. 2023;1:166-75.
[4] Lu J, Wang X, Liu H, Yu H, Li W. Optimizing operation of municipal wastewater treatment plants in China: The remaining barriers and future implications. Environ Int. 2019;129:273-278.
[5] Foley J, Haas D, Yuan Z, Lant P. Nitrous oxide generation in full-scale biological nutrient removal wastewater treatment plants. Water Res. 2010;44:831-844.
[6] Pijuan M, Tora J, Rodriguez-Caballero A, Cesar E, Carrera J, Perez J. Effect of process parameters and operational mode on nitrous oxide emissions from a nitritation reactor treating reject wastewater. Water Res. 2014;49:23-33.
[7] Harris S, Weinzettel J, Bigano A, Källmén A. Low carbon cities in 2050? GHG emissions of European cities using production-based and consumption-based emission accounting methods. J. Cleaner Prod. 2020;248:119206.
[8] Vourdoubas I. Creation of zero carbon emissions wastewater treatment plants - A case study in crete, Greece. Energy Environ. Res. 2018;8(1):64-72.
[9] Ministry of Housing and Urban-Rural Development, China urban construction statistical yearbook. 2021.
[10] IPCC. IPCC Guidelines for National Greenhouse Gas Inventories. 2006.
[11] Ministry of Ecology and Environment, Annual statistic report on environment in China. 2021.
[12] Liu Y, Ni B, Ganigue R, Werner U, Sharma K, Yuan Z. Sulfide and methane production in sewer sediments. Water Res. 2015;70:350-359.
[13] Short M, Daikeler A, Wallis K, Peirson W, Peters G. Dissolved methane in the influent of three Australian wastewater treatment plants fed by gravity sewers, Sci. Total Environ. 2017;600:85-93.
[14] Short M, Daikeler A, Peters GM, Mann K, Ashbolt NJ, Stuetz RM, Peirson WL. Municipal gravity sewers: an unrecognised source of nitrous oxide. Sci. Total Environ. 2014;469:211-218.
[15] Eijo-Río E, Petit-Boix A, Villalba G, Suárez-Ojeda ME, Marin D, Amores MJ, Aldea X, Rieradevall J, Gabarrell X. Municipal sewer networks as sources of nitrous oxide, methane and hydrogen sulphide emissions: A review and case studies. J. Environ. Chem. Eng. 2015;3:2084-2094.
[16] Chen Y, Kuo J. Potential of greenhouse gas emissions from sewage sludge management: a case study of Taiwan. J. Cleaner Prod. 2016;129:196-201.
[17] Alshboul Z, Encinas-Fernandez J, Hofmann H, A. Lorke. Export of dissolved methane and carbon dioxide with effluents from municipal wastewater treatment plants. Environ Sci Technol. 2016;50: 5555-5563.
[18] Gonzalez-Valencia R, Sepulveda-Jauregui A, Martinez-Cruz K, Hoyos-Santillan J, Dendooven L, Thalasso F. Methane emissions from Mexican freshwater bodies: correlations with water pollution. Hydrobiologia. 2013;721:9-22.
[19] Solon K, Volcke EIP, Spérandio M, van Loosdrecht MCM. Resource recovery and wastewater treatment modelling. Environ. Sci.: Water Res. Technol. 2019;5:631-642.
[20] Sun Y, Chen Z, Wu G, Wu Q, Zhang F, Niu Z, Hu H. Characteristics of water quality of municipal wastewater treatment plants in China: implications for resources utilization and management. J. Cleaner Prod. 2016;131:1-9.
[21] Østergaard PA, Andersen AN. Booster heat pumps and central heat pumps in district heating. Appl. Energy. 2016;184:1374-1388.