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Analysis of Greenhouse Gas Emission Factors and Influencing Factors in Wastewater Treatment Processes

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ABSTRACT: With the proposal of carbon neutrality goals, the high energy consumption and significant greenhouse gas emissions caused by traditional wastewater treatment processes have attracted widespread attention. Research on carbon emissions during wastewater treatment has become a hot topic. In this context, wastewater treatment plants need to achieve not only water resource sustainability but also carbon reduction. Precisely monitoring and evaluating the carbon emission levels of urban drainage systems and wastewater treatment plants, and scientifically proposing wastewater treatment carbon reduction paths and carbon neutrality models, are key breakthrough points for urban water pollution control to achieve the “carbon peak, carbon neutrality” goals, and are also the cutting-edge and focus of current environmental science and technology. This paper takes urban drainage systems and wastewater treatment plants as the main objects, summarizes the current research status of greenhouse gas emission monitoring and quantitative assessment, discusses and analyzes the main sources, emission status, and influencing factors of greenhouse gases in wastewater treatment plants.

KEYWORDS: Carbon Emissions; Wastewater Treatment Plants; Greenhouse Gases

0. INTRODUCTION

The current obstacles to environmental sustainability mainly come from frequent natural disasters and environmental deterioration caused by global warming. CO_2, CH_4, and N_2O released into the atmosphere through traditional wastewater treatment are the main gases causing the greenhouse effect [1]. Statistical data from industrialized countries show that the wastewater treatment industry is one of the top ten carbon-emitting industries. Wastewater treatment plants generate greenhouse gas emissions, accounting for about 1.6% of global greenhouse gas emissions to the atmosphere, and are an important area for carbon reduction. According to the latest forecasts by the United Nations, the global population will reach 9.7 billion by 2050, with nearly 70% of the population living in urban areas[2]. The rapid population growth and concentration are having a profound impact on resource and energy demand and industrial manufacturing. Over the past century, urban wastewater collection and treatment systems have played a crucial role in ensuring public health and safety. Water is a fundamental resource for human survival and development, and wastewater treatment facilities have also become one of the most energy-intensive public facilities, accounting for 1% to 3% of total social energy consumption. According to the U.S. Environmental Protection Agency, by 2030, global CH_4 and N_2O emissions from wastewater treatment will be close to 600 million tons and 100 million tons of CO_2 equivalent, respectively, accounting for 4.5% of all non-CO_2 emissions. Therefore, implementing carbon reduction projects in wastewater treatment plants has significant economic and social value. [3]

1. Analysis of Carbon Emissions in the Wastewater Treatment Process

The direct and indirect carbon emissions of the wastewater treatment process are distinguished according to the emission mode. The process of removing pollutants from wastewater through biological methods usually releases CO_2, CH_4, and N_2O. However, according to the standards of the Intergovernmental Panel on Climate Change (IPCC) [4], because the direct emission of CO_2 in wastewater treatment plants is a short-term carbon emission behavior, its impact on global warming is small. In addition, all energy consumption caused by the use of energy (including electricity), chemicals, and materials belongs to the category of indirect carbon emissions.

1.1 Emission Pathways

Based on relevant literature, the greenhouse gases produced by different processes or reactors in wastewater treatment plants include but are not limited to CH_4, N_2O, and CO_2.

1.1.1 CO_2 Emission

The CO_2 emissions during the wastewater treatment process are related to microbial activity, energy consumption, and chemical use. Activated sludge decomposes and removes organic pollutants in wastewater through biological flocculation, adsorption, and oxidation. The respiration of activated sludge provides energy for its growth and reproduction, and this process inevitably produces CO_2, but most of the CO_2 is produced by the degradation of organic matter by microorganisms, rather than respiration. The principles and contents of CO_2 emissions from different regions of different reactors are also different. The largest area, the sedimentation tank, emits the least CO_2 because the respiration of microorganisms is weak and biological activity is limited.

1.1.2 CH_4 Emission

As one of the hotspots of greenhouse gas research, CH_4 contributes 28 times more to global warming than CO_2. The total CH4 emissions from wastewater treatment plants are 72% from sludge facilities, and the rest come from different biological reactors, with roughly the same emission trends [5]. A comprehensive investigation of the greenhouse gas emissions of an AAO wastewater treatment plant in China for 9 months showed that the CH_4 emissions in the early aerobic zone were significantly higher than those in the anaerobic zone, which contradicts the theory that CH_4 should be produced under anaerobic conditions. Because CH_4 is not only produced under anaerobic conditions in sludge facilities (such as sludge thickening tanks and sludge storage tanks), but also released through stripping in the aeration zone.

1.1.3 N_2O Emission

The concentration of N_2O in the atmosphere is increasing year by year, and if its concentration doubles, the global temperature will rise by 0.3°C. N_2O is an important contributor to greenhouse gas emissions. Of the increased carbon footprint during the biological treatment of wastewater, 78.4% comes from the direct emission of N_2O in the anaerobic zone [6]. Therefore, understanding the causes of N_2O production and its proportion in the total carbon emissions is crucial for carbon reduction. During the denitrification process of wastewater, a large amount of N_2O is produced and released into the atmosphere by biological denitrification. Although N_2O is not the main intermediate product of nitrification, the denitrification or incomplete denitrification of nitrifying bacteria can also lead to N_2O emissions. Although the processes are different, studies have shown that N_2O emissions are generally the highest in the aerobic zone, followed by the anoxic zone . At present, further comprehensive research is needed to further clarify the emission mechanism of N_2O and increase understanding of N_2O emissions from wastewater treatment plants.

1.2 Emission Classification

Xie Tao et al. [7] divide greenhouse gas emissions in wastewater treatment into three parts: direct emissions, indirect emissions, and other indirect emissions. Direct carbon emissions are the carbon emissions associated with relevant biochemical reactions during the treatment process, including the emission of CH_4 under anaerobic conditions and the emission of N_2O by denitrifying bacteria under aerobic conditions. Indirect carbon emissions are the carbon emissions corresponding to energy consumption during wastewater treatment, including the carbon emissions generated by the electricity consumption of equipment, chemical addition, and sludge transportation in the wastewater treatment process, which are calculated by multiplying the monthly consumption by the corresponding carbon emission factor. The accounting of carbon emissions in the wastewater treatment system is a complex process with many links and processes. It not only needs to consider the production and release of greenhouse gases in different units and links but also involves storage and recovery.

1.3 Influencing Factors

In a complex biological reaction process, due to the mutual influence of different environmental factors and the limitations of existing measurement methods, it is challenging to develop mitigation strategies for greenhouse gas emissions based on the amount of carbon emissions. Therefore, future research needs to further study the impact indicators of greenhouse gas emissions and their interrelationships.

1.3.1 Influent Quality

The amount of greenhouse gas emissions during wastewater treatment is closely related to the influent quality. Comparing two different wastewater treatment plants' reports pointed out that one of the main reasons for the difference in their energy intensity (0.45 kWh/m3 and 0.40 kWh/m3, respectively) is the different influent quality. In addition, salinity is also a key parameter affecting the amount of greenhouse gas emissions. It has been reported that NO_2 concentration is positively correlated with N_2O production, but it inhibits N_2O production in some partial nitrification reactors [8]. In aerobic-anaerobic experiments, the increase in N_2O release is mainly due to the migration of oxygen from the aerobic zone to the anoxic zone due to high salinity when nitrification is weakened. In addition, salinity also directly affects enzyme activity, especially N_2O reductase.

1.3.2 Dissolved Oxygen Concentration

Dissolved oxygen (DO) concentration is one of the factors affecting the amount of greenhouse gas emissions. Studies have found that when the concentration and oxygen consumption of organic matter in the influent are low and the DO content is high, the N_2O emissions mainly come from the dissolved N_2O in the influent; with the gradual increase of organic matter in the water, the DO content is significantly reduced, and when incomplete nitrification reaches a certain degree, a large amount of N_2O appears. In addition to the low DO content in conventional nitrification and denitrification processes promoting N_2O emissions, high DO content in the anoxic zone also inhibits N_2O emissions. In addition, high concentrations of CH_4 are produced in the anoxic zone, while its concentration becomes lower in the aerobic zone, indirectly proving that the increase in DO content also has an inhibitory effect on CH_4 production. In addition to affecting the gas production mechanism, reducing the DO setpoint can bring energy savings that account for 6% to 10% of the total energy used for aeration each year. [9]

1.3.3 Process Selection

The carbon emission situation of different processes is different. When the environment changes, bacteria may need some time to adapt to this change, leading to a large amount of greenhouse gas emissions. A study compared the carbon emission situations of three full-scale wastewater treatment processes: oxidation ditch, reverse AAO, and AAO. Among them, the AAO process has the highest CO_2 emission factor and the most greenhouse gases are produced per m3 of wastewater (0.183 kg CO_2 equivalent). Depending on the treatment scale and technology, the electricity consumed by traditional activated sludge processes to treat wastewater ranges from 0.36 kWh/m^3 to 1.26 kWh/m^3[10]. Compared with traditional denitrification processes, the anammox process can reduce 60% of energy consumption and 90% of greenhouse gas emissions, and switching from a traditional nitrification/denitrification unit to an anoxic unit can reduce 17 kg of CO_2 equivalent (coal-fired) and 10 kg of CO_2 equivalent (natural gas-fired).

2. Carbon Emission Accounting Methods

Internationally, there are two methods to monitor greenhouse gas emissions: accounting methods and measurement methods. The European Union places the accounting method and the measurement method on an equal footing, the United States gives priority to the measurement method, and China currently mainly uses the accounting method. At present, the commonly used research methods for carbon emission accounting in wastewater treatment are direct measurement, emission factor method, mass balance method, carbon footprint method, and model method [11]. Specific introductions are as follows:

2.1 Direct Measurement Method

The direct measurement method (Experiment Approach), also known as the sampling measurement method, is based on the field measurement data of the emission source to obtain the relevant carbon emission data. That is, a sampling point is set up in the wastewater treatment plant for monitoring, and the carbon emission data of the wastewater treatment plant is calculated according to the measurement data. This method can also calculate the corresponding greenhouse gas emission coefficients of the wastewater treatment plant. This method has fewer intermediate links and accurate results, but the data acquisition is relatively difficult and requires a large investment. In reality, the samples collected on-site are often sent to relevant monitoring departments, and special detection equipment and technology are used for quantitative analysis. Therefore, this method is also affected by factors such as sample representativeness and measurement accuracy involved in the sample collection and processing process. Due to the lack of basic data on actual wastewater treatment plant carbon emissions in China, the application of the measurement method in China is not yet widespread [12].

The calculation formula for methane (CH_4) emissions from domestic wastewater is as follows:

$CH4 = (TOW \times EF) - R$

Where:

CH_4 ——the total methane emissions from domestic wastewater, measured in kg CH4/year;

TOW——the total organic matter emissions from domestic wastewater, measured in kg BOD/year;

EF——the emission factor for wastewater treatment, measured in kg CH_4/kg BOD;

R——the amount of methane recovered (kg CH_4), with a default value of 0.

2.2 Emission Factor Method

The emission factor method (Emission-Factor Approach), also known as the emission coefficient method, is the first carbon emission estimation method proposed by the IPCC. Its basic idea is to construct the activity data and emission factor for each emission source according to the carbon emission inventory list, and use the product of activity data and emission factor as the estimated value of carbon emissions from the emission source [13]. Existing inventory calculations are all based on activity data and emission factors, that is, the coefficient accounting method is used for carbon emission measurement:

$$\mathbf{E = A \times EF \times (1 - ER/100)}$$

where:

E —— the amount of greenhouse gas emissions;

A ——the activity data of greenhouse gas emissions, which specifically refers to the amount of greenhouse gas directly related to carbon emissions from a single emission source. The data mainly come from national statistical data, emission source censuses and survey data, monitoring data, etc.;

EF ——the emission factor, such as the amount of greenhouse gas emissions per unit of energy consumption [14];

ER——the reduction rate (%).

2.3 Mass Balance Method

The mass balance method (Mass-Balance Approach) is a new method proposed in recent years to calculate the input, output, production, consumption, and conversion balance of materials and energy in the process. It mainly calculates the carbon dioxide emission based on the chemical balance equation. According to the new chemicals and equipment used for national production and life each year, the share of new chemicals consumed to meet the capacity of new equipment or to replace and remove gases is calculated. The advantage of this method is that it can reflect the actual emission of carbon emissions at the place of occurrence, not only can distinguish the differences between various facilities, but also can distinguish the differences between individual and partial equipment; especially when equipment is constantly updated year by year, this method is simple to calculate. The mass balance method is a method proposed based on the law of conservation of mass, which calculates the carbon dioxide emission equivalent by subtracting the carbon content in the output material from the carbon content in the input material. The carbon emission calculation formula is as follows:

$$E = [\Sigma(M_i \times C_i) - \Sigma(M_j \times C_j)] \times \omega \times GWP$$

where:

E —— the carbon dioxide emission equivalent;

M_i ——the amount of input material;

C_i ——the carbon content of input material;

M_j —— the amount of output material;

C_j ——the carbon content of output material;

ω——the conversion coefficient corresponding to the transformation of the mass of input carbon elements into carbon dioxide;

GWP ——the global warming potential, and the value can be referred to the data provided by the IPCC.

2.4 Carbon Footprint Method

The concept of carbon footprint originates from "ecological footprint" and represents the total amount of greenhouse gases emitted during human production and consumption activities. Carbon footprint analysis is a new measurement method based on life cycle assessment (LCA) to calculate the impact of carbon emissions, which reveals the carbon emission process of different objects from the perspective of the life cycle. It specifically measures the direct and indirect carbon emissions related to a certain product throughout its life cycle or a certain activity process, providing a scientific basis for exploring reasonable and effective greenhouse gas reduction paths. At present, the main carbon footprint calculation methods include input-output life cycle assessment, process life cycle assessment, and mixed life cycle assessment.

2.5 Model Method

At present, Logistic model, Leap model, and CGE model are common models used for carbon emission estimation [15]. The former is a relatively single carbon emission measurement model, mainly for prediction through data analysis and calculation; the latter two are scenario analysis models, which obtain prediction results by comprehensive scenario analysis of future carbon emissions. In addition, IPAC model and MARKAL-MACRO model are widely used in carbon emission simulation. At present, there is a lack of detailed and comprehensive research on the carbon emission situation of wastewater treatment and carbon emission accounting models.

2.6 Comparison of Carbon Emission Accounting Methods for Different Treatment Processes

Table 1 Comparison of carbon emission accounting methods

Method	Principle	Advantages and Disadvantages
Direct Measurement	Continuous real-time measurement of point sources	Intermediate steps are few, calculation results are closest to the true value; Data acquisition difficulty and high cost, and monitoring results are easily affected by sample and instrument accuracy
Emission Factor	Based on statistical data	Easy to grasp, complete data and many reference examples; Large uncertainty of emission factors for different processes
Mass Balance	Calculation based on the law of conservation of mass	Wide application scope, easy data collection, and simple method
Model	Simulate carbon emission process	Applicable to specific

3. CONCLUSION

There are many sources of CO_2 emissions from wastewater treatment plants, including the degradation of COD in the wastewater and the energy consumption of mechanical equipment. Previous research on carbon emissions has mainly relied on estimation and prediction, which cannot reflect the actual reactions of carbon emissions. When conducting specific accounting, it is necessary to understand the actual carbon emissions of typical urban wastewater treatment plants in China under the influence of temporal and spatial distribution, as well as environmental and climatic conditions such as temperature and wind speed. [16]

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