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Calculation of Sludge Carbon Emissions under Different Disposal Methods

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Abstract. Due to the different carbon emissions of sludge disposal methods, this article calculates the carbon emissions of sludge under two different disposal methods: "drying+incineration" and "sanitary landfill" for 2 tons of sludge. The accounting results show that the carbon emissions generated by the "drying+incineration" process only account for 25.3% of the "sanitary landfill" process, and the treatment of sludge through the "drying+incineration" method has a significant carbon reduction effect. At present, global carbon dioxide emissions are getting higher and higher, pollution is becoming more and more serious, pollutant harmless treatment and environmental governance is urgent, this paper can clearly know the results of different disposal methods through different ways of carbon emission accounting, so as to choose the most appropriate method to deal with pollutants, achieve harmless treatment, protect the environment, and also provide a new feasible solution for carbon emission disposal for people to choose and contribute to environmental governance.

Keywords: sludge disposal, Drying and incineration, security landfill, Carbon emissions accounting

1. Introduction

1.1. Research status of carbon emissions from sludge treatment and disposal

At present, the technological level of urban sewage treatment in China lags far behind that of foreign countries. However, due to the increase in energy consumption and waste production in the urban sewage treatment industry, the emission of CO_2 in sewage is also on the rise, and sewage treatment plants have gradually become the world's largest source of CO_2 emissions [1]. In the context of the national "dual carbon" policy, the reduction of urban household waste is increasingly attracting people's attention. At present, corresponding carbon emissions measurements have been made for different wastewater treatment processes both domestically and internationally. For example, Wuxi city has conducted carbon emissions measurements for wastewater treatment processes, providing a good reference for low-carbon and renewable utilization of wastewater treatment processes in the future. The research on carbon footprint accounting and low-carbon collaborative pollution reduction control technology in the sewage treatment industry also proposed the measurement idea of "industrial carbon emission reduction", but the understanding of it is not deep enough at present.

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The implementation of this project will enhance the scientific, standardized, and operable calculation of China's total solid waste emissions, strengthen data transparency, unified format, and comparability of results, provide data and technical support for applications such as total solid waste emissions calculation, carbon peak emission reduction, and greenhouse gas emission reduction, and promote the development of solid waste emissions calculation and related industries [2].

1.2. The purpose and significance of accounting

China is the world's largest emitter of CO_2, with 25% of the world's CO_2 emissions, but its CO_2 emissions from domestic wastewater are only 1% -2%. In short, solid waste is an important aspect that cannot be ignored in the development process of our country. The treatment technology of solid waste is an important component of solid waste. Therefore, establishing a reasonable design method for sewage treatment plants is the key to achieving low-carbon sewage treatment plants. The research results can contribute to the research and development of low-carbon and low-carbon technologies for urban sewage treatment plants in China, as well as the scientific operation of enterprises, proposing more reasonable sewage treatment processes and laying a theoretical and technical foundation for the development of urban sewage treatment plants [3].

2. Analysis of carbon emission processes from different sludge disposal methods

At present, China mainly uses landfill, land reuse, and building materials methods to treat household waste, and uses various methods such as incineration, composting, hydrothermal hydrolysis, and anaerobic bacteria to dispose of household waste. Among these technologies, significant achievements have been made in reducing the incineration of urban household waste, harmless treatment, and recycling waste heat. Due to its advantage as a raw material, it has gradually replaced the landfill of domestic wastewater and formed a new type of sludge treatment method. The article only analyzes its CO_2 reduction effect from the perspectives of combustion and landfill.

2.1. Landfill

At present, qualified waste from urban sewage treatment plants in China accounts for 31% of the total landfill volume, which is lower than the 40% of qualified waste and difficult to accurately calculate. Conventional urban household waste is mainly landfilled in anaerobic form, producing 64% methane and 35% carbon dioxide. In landfills, CH_4 is mainly generated through methane production. CO2 emissions occur during the acidic stage of the entire landfill site. One ton of sludge in compost will produce about 500 kg of carbon dioxide [4].

Landfilling is one of the main pathways for CH_4 release, accounting for approximately 10% -19% of global CH_4 emissions. In the IPCC, landfill methane (CH_4) is listed as an important measure to reduce household waste emissions. The most intuitive way is to reduce methane emissions and accelerate methane oxidation rate through on-site regulation. This project plans to use aerobic landfill instead of conventional anaerobic landfill to reduce CH_4 yield by 72% -96% and achieve energy recovery, but indirect CO_2 emissions due to operational energy consumption. However, it is still unclear whether the energy utilization of aerobic landfills can compensate for the carbon deposition effect caused by energy consumption in landfills [5]. Organic covering of soil can effectively reduce the release of biogas, with soil and compost as the main coverings. These coverings contain a large number of aerobic methane oxidizing bacteria, which can promote the oxidation of CH_4 produced inside the landfill to CO_2 during the outward diffusion process. Research

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has shown that the CH_4 oxidation rate of soil and compost cover ranges from 10% to 100%. Soil texture and compaction strength can affect CH_4 oxidation efficiency. The experimental results show that when covering soil and composting, the biogas oxidation rate can reach 10% -100%; The soil properties and compaction degree have a certain impact on the methane oxidation rate. The results indicate that when the particle size of the covering soil is large, its oxidation rate of methane is higher, while its compaction degree is lower; The compaction strength of sandy clay is improved in sandy clay, but the compaction strength is higher in sandy clay than in sandy clay. In sandy soil, loam, clay, and clay, the methane oxidation rates are 53%, 34%, and 18%, respectively. This is due to the differences in pore properties of gravel with different sizes and densities. When the porosity of the gas is less than 10%, its discontinuous and tortuous pores will seriously affect the efficient conversion of methane and oxygen. The permeability of the gas is directly proportional to the permeability of the gas and the oxidation rate of methane.

2.2. Incineration

Sludge incineration refers to the process in which combustible substances in sludge are completely burned in an incinerator by increasing the temperature, producing harmless substances such as water vapor and CO_2, and producing solid residue. Due to its high efficiency, minimal pollution, and thorough treatment, it is widely used in various fields [6]. However, due to its high operating costs, low degree of resource utilization, and strong toxicity in the exhaust gas and residue generated after combustion, it has brought great inconvenience to urban life. Sludge incineration technology mainly includes individual incineration, collaborative incineration of garbage, and collaborative disposal of cement kilns. At present, the main methods for treating urban sewage in China are a combination of blade drying, fluidized bed drying, and fluidized bed combustion. Through experiments and theoretical analysis, it is concluded that the moisture content, residence time, and combustion reaction temperature of sludge are the main factors determining the efficiency of garbage incineration. In general, the excess air coefficient and other factors require a sludge moisture to volatile matter ratio of less than 3.5, a sludge moisture content greater than 35%, an incineration temperature greater than 850 ℃, a combustion shutdown time greater than 2 seconds, and a flue gas shutdown time greater than 3 seconds [7].

During the process of sludge combustion, NOx, SO_2, and HCl are the main pollutants emitted; Particulate matter, heavy metals, dioxins, and other pollutants. The characteristics of smoke and dust after sludge incineration in China's sewage treatment process were analyzed [8], and the results showed that NOx, SO_2, and HCl were the largest pollutants in the smoke and dust after incineration in the sewage treatment process; The content of particulate matter is 50-300 mg/m^3, the content of heavy metals is 2000-5000 mg/m^3, and the content of dioxins is 50-300 mg/m^3 [9]. The concentration of flue gas generated during coal combustion in our country is high and the harm is significant. Effective treatment is needed to meet the requirements of the "Pollution Control Standards for Municipal Solid Waste Incineration" and reduce secondary pollution.

3. Carbon emission accounting for different disposal methods of sludge

3.1. Accounting process

Determine a reasonable accounting boundary based on the different carbon emission characteristics of sludge disposal methods.Determine the method for carbon emission accounting of different

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sludge disposal methods.Based on the accounting method, carbon from different sources in various sludge treatment and disposal processes is accounted for [10].

3.2. Determination of accounting boundaries

Establishing a scientific quantification threshold is a prerequisite for the full-process low-carbonization of urban domestic water use. To ensure and enhance measurement accuracy, it is imperative to scientifically delineate different measurement ranges. Each process must be carefully considered to avoid duplication and omissions [11].

Based on different sludge disposal methods [12], multiple routes can be arranged. This article conducts carbon emission accounting for two of these routes:R1:Concentration and dehydration and transportation and drying and incineration and utilization as building materials;R2:Concentration and dehydration and transportation and sanitary landfill.

Based on this, the secondary sedimentation tank of the wastewater was separated and enriched, and the products were analyzed in detail in terms of their form of output or energy form. In order to accurately compare the carbon emissions under various sludge treatment and disposal technology paths, 2 tons of dry sludge (DS) were taken as the accounting object. According to the types of emissions, it was divided into two stages, and the direct and indirect carbon emissions were calculated separately.

In these processes, the main direct carbon sources include: coal combustion sources and mobile sources, domestic waste landfill sources and anaerobic sources, as well as CH_4 and N_2O produced through aerobic fermentation.

Indirect carbon emissions refer to the carbon dioxide generated within the boundaries of an enterprise, such as the electricity required for production processes, the heat required for drying and hydrolysis (assuming it is purchased from external sources), and the chemicals required for sludge dewatering [13].

3.3. Determination of carbon emission accounting method

3.3.1. Direct emissions

In the atmosphere, besides CO_2, gases such as methane, nitrogen oxides, and sodium hydroxide are also produced. Currently, China has incorporated major greenhouse gases such as PCFs and SF into its national environmental impact assessment system. Their contribution to global environmental impact varies depending on factors such as their lifecycle and radiation levels. Based on this, the CO_2 equivalent calculation method was employed to analyze the impact of different CO_2 equivalents on the overall carbon emissions of the entire wastewater treatment system. Specific conversions can be made using formula (1).

$$AE = AD \times GWP \times EF \tag{1}$$

In this context, GWP refers to the values required by the IPCC Fifth Assessment Report, specifically the global warming potentials (GWP) at the 100-year level for greenhouse gases (CO_2, CH_4, and N_2O) involved in sludge treatment and disposal, as detailed in Table 1 below.

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Table 1. Global Warming Potential (GWP) values of greenhouse gases

Types of greenhouse gases	CO_2	CH_4	N_2O
GWP	1	28	265

3.3.2. Indirect emissions

The emission factor method is employed for indirect emissions, where the carbon emissions are calculated by multiplying the data consumed by an activity with the empirical coefficient (emission factor) corresponding to the quantified unit of activity emissions and show in Table 2.

$$E = D \times EF \tag{2}$$

Table 2. Indirect emission factors

D activity consumption		EF emission factor	Source of emission factors
electricity		0.5839 kg·(kW·h)$^{-1}$	literature [14]
thermal power		110 kg·GJ^{-1}	literature [15]
medicine	PAM	25 kg·kg^{-1}	literature [16]
	$FeCl_3$	8.3 kg·kg^{-1}	literature [16]
	CaO	1.4 kg·kg^{-1}	literature [16]

Based on this, through the analysis of urban domestic waste incineration for power generation, the CO2 emission values from urban domestic waste incineration for power generation were obtained. The energy structure varies across different regions, resulting in significant differences in the power emission factors between regions. In 2015, the average power emission coefficient nationwide was 0.6101 kg·(kW·h)$^{-1}$. In this paper, the latest revised value of 0.5839 kg·(kW·h)$^{-1}$ from 2022 is adopted for calculation (a decrease of approximately 4.3% compared to 2015). According to the calculations conducted by the National Development and Reform Commission for various industries, the corresponding thermodynamic carbon emission factor is 110 kg·GJ^{-1}. In the sludge treatment process, dehydration agents consisting mainly of $FeCl_3$, CaO, and polyacrylamide (PAM) need to be added. The input amounts and other direct emission energy consumption are shown in Table 3.

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Table 3. Summary of indirect emission energy consumption across different process units

processing unit	project	Parameters (in DS)	Remarks	Source of emission factors
gravity concentration	power consumption	13 kW·h·t^{-1}	water content 97%	literature [17]
frame filter dehydration	power consumption	40 kW·h·t^{-1}	water content 80%	literature [17]
	$FeCl_3$ dosage	30 kg·t^{-1}		literature [16]
	CaO dosage	50 kg·t^{-1}		literature [16]
deep dehydration	power consumption	125 kW·h·t^{-1}	water content 60%	literature [17]
	PAM dosage	10 kg·t^{-1}		literature [18]
	$FeCl_3$ dosage	6%		literature [18]
	CaO dosage	10%		literature [18]
dry heat	power consumption	10 kW·h·t^{-1}	water content 80%-40%	literature [19]
	heat consumption	9.16 GJ·t^{-1}		theoretical calculation
incineration	electric power consumption of incinerator	300 kW·h·t^{-1}	Large-scale high-efficiency fluidized bed incinerator	literature [20]

3.4. Calculation of carbon emissions for different routes

3.4.1. Calculation of carbon emissions from incineration routes

R1:Gravity concentration + plate and frame filter press dewatering and transportation and drying and incineration and building material utilization.

The calculation of carbon emissions for this route primarily focuses on the greenhouse gas emissions involved in three stages: transportation, drying, and incineration.

During the transportation of sludge, vehicles are inevitably used, and the combustion of fossil fuels during this process will directly release carbon dioxide. Most large heavy-duty trucks are diesel-powered, and their diesel consumption is estimated based on the transportation distance, as shown in formula (3). Assuming a distance of 20 km, a 10-ton truck consumes approximately 10 liters of diesel per 100 kilometers.

$$RL = \frac{m}{(1-w)M} \times L \times AVG \times \rho_1 = 8.4\text{kg} \tag{3}$$

$$E_{CO_2} = RL \times RZ \times C \times \alpha \times \frac{44}{12} \times 10^3 = 2.64 \times 10^9 kg \tag{4}$$

After mechanical dewatering, its moisture content can exceed 80%, but since it cannot spontaneously combust, further drying is required. Only when it reaches a certain moisture content can it be entered into the furnace for incineration. Different initial and final moisture contents have a significant impact on the energy consumption of thermal drying. Calculations are based on a 40% moisture content after drying is completed, mainly including three aspects: first, the heat absorbed by the solid slurry during temperature rise; second, the heat absorbed by evaporating water; and third, the calculation of theoretical thermal energy consumption for thermal drying.

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$$Q_S = \left(T_2 - T_1\right) \times C_S \times m \times 10^{-3} = 579.2 \times 10^{-3} GJ \tag{5}$$

$$M_W = \left(\frac{m}{1-w_1} - \frac{m}{1-w_2}\right) \times 10^3 = 6.67 \times 10^3 kg \tag{6}$$

$$Q_w = C_w \times \frac{mw_1}{1-mw_1} \times \left(T_2 - T_1\right) \times 10^6 + Q_g \times M_w \times 10^{-6} = 2275.074 \times 10^{-6} GJ \tag{7}$$

$$E_{hotdry} = (Q_s + Q_w) \times EF_{hot} \times 10^{-3} \tag{8}$$

$$E_{\mathrm{CO_2}} = m \times CF \times FCF \times OF \times \frac{44}{12} = 0.396 kg \tag{9}$$

total carbon emissions =3.63×109 kg

3.4.2. Calculation of carbon emissions from sanitary landfill routes

R2 is Gravity concentration and plate and frame filter press dewatering and transportation and sanitary landfill.

The carbon emission accounting for this route primarily focuses on the greenhouse gas emissions involved in two aspects: transportation and sanitary landfill. The calculation of carbon emissions in the transportation phase is identical to that of the R1 route, with an emission volume of 2.64×10^6 kg.

$$M_{CH_4,sanitarylandfill} = m \times DOC \times DOC_f \times MCF \times F \times \frac{16}{12} \times (1 - OX) \tag{10}$$

$$E_{CH_4,sanitarylandfill} = m \times DOC \times DOC_f \times MCF \times F \times \frac{16}{12} \times (1 - OX) \times (1 - MCR) \times G_{CH_4} \tag{11}$$

total carbon emissions = 3.67×10^9 kg

3.4.3. Comparison of carbon emissions between two disposal routes

The total carbon emission from treating 2 tons of DS via the R1 route is 3.63×10^9 kg, with the thermal drying and incineration stages being the primary sources of carbon emissions. According to the data, when the moisture content of 2 tons of DS decreases from 80% to 40%, the heat consumption during the sludge drying stage is 579.2×10^{-3} GJ·t^{-1}. Since the moisture content of sludge directly affects the heat consumption during drying, reducing the amount of water evaporated before drying ultimately achieves the goal of reducing the carbon dioxide produced during the sludge drying process.

The total carbon emissions for processing 2 tons of DS via the R2 route are 3.67×10^9 kg. The primary carbon emission pathway is through sanitary landfill, which involves significant carbon emissions and requires a large amount of land. Additionally, it generates some secondary pollution, such as odors and accumulated leachate.

4. Conclusion

The treatment methods for sludge vary depending on the sludge treatment approach. Carbon emissions were calculated for two disposal routes for 2 tons of sludge, primarily involving "drying + incineration" and "sanitary landfill". The carbon emissions generated by the "drying + incineration"

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process in Route R1, amounting to 0.396006396 kg, are significantly lower than the carbon emissions generated by the "sanitary landfill" process in Route R2, which amount to 1.568 kg. The carbon emissions generated by the "drying + incineration" process account for only 25.3% of those generated by the "sanitary landfill" process, indicating that treating sludge through the "drying + incineration" method has a notable carbon reduction effect.

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