Comparison of Carbon Emissions in Different Sludge Treatment Pathways - a Case Study of Jiaxing, China

Lijun Wu[1, 2, 3], Junjie Li[1, 4*], Chengwei Feng[5], Fenfei Chen[1, 4], Jianhang Li[1, 4] and Qi Zhang[4]

[1] Power China Huadong Engineering Corporation Limited, Hangzhou 311122, Zhejiang, China
[2] College of Environmental and Resource Science, Zhejiang University, Hangzhou 310029, Zhejiang, China
[3] Huadong Eco-Environmental Engineering Research Institute of Zhejiang Province, Hangzhou 311122, Zhejiang, China
[4] Yangtze River Delta (Jiaxing) Ecological Development Co., Ltd., Jiaxing 314000, Zhejiang, China
[5] Haining Smart Environmental Protection and Solid Waste Pollution Prevention and Control Center, Jiaxing 314400, Zhejiang, China

Abstract. Sludge management strategy is essential to future carbon reduction in wastewater plants since the treatment and disposal of sludge contribute significantly to the carbon emissions. Using the method proposed by intergovernmental Panel on Climate Change(IPCC), the three sludge treatment paths of a typical wastewater treatment plant in Jiaxing were investigated. The result showed that net carbon emission is negative at -588kgCO_2/tDS thanks to R3 which is characterized by centrifugal dehydrator, coal blending incineration with combined heat and power generation and cement substitute by slag is the rout with lowest carbon missions. The carbon emission of R1 is the highest at 699.87 kgCO_2/tDS because of the chemical reagents. Process unit with larger carbon emissions was identified to be dewatering in which chemical reagent contributed the most. The main carbon offsets was the combined heat and power cogeneration which should be widely advocated.

1 Introduction

Global warming has become a growing concern in recent decades. China's dual carbon target, first proposed at the 75th session of the United Nations General Assembly in September 2020,was to reach its CO_2 emissions peak before 2030 and attain carbon neutrality by 2060. To achieve this goal, it is necessary to quantify the carbon emissions of each industry using scientific accounting methods. The National Development and Reform Commission (NDRC) has developed accounting methods and reporting guidelines for several key industries: power generation, power grids, iron and steel, chemicals and cement, etc. However, relatively little research has been done on carbon accounting for the wastewater and sludge treatment industries. With the improvement of water quality standards in recent years, energy consumption and sludge production in the wastewater treatment industry has been increasing, along with its carbon emissions. [1]Wastewater treatment plants (WWTPs) have gradually become one of the main sources of greenhouse gases, according to statistics, 0.3% of China's total annual electricity consumption is used for wastewater treatment plants, releasing approximately 11.4 billion t CO_2 equivalent. As it is difficult to offset the carbon emissions caused by the necessary energy consumption during the wastewater treatment process, one feasible way to complete the overall carbon neutrality of the wastewater treatment industry is to recycle the resources contained in the sludge. Different sludge treatment and disposal technology routes have different energy consumption and different levels of sludge resource utilization, so the carbon emissions generated will vary. the final destination of urban sludge in China is mainly sanitary landfill, land use, building materials use, incineration, composting, thermal hydrolysis and anaerobic digestion are the mainstream technologies for sludge treatment in China[2]. At present, the incineration technology has the advantages of significant reduction, complete harmlessness, waste heat recovery and ash recovery for building materials.

This study conducted a systematic calculation of the carbon emissions related to sludge treatment pathways of a wastewater treatment plant in Jiaxing, China with an aim to provide guidance on greenhouse reduction potentials and reference on sludge treatment pathway selection and optimization.

2 Material and Methods

2.1 Accounting Boundary

The starting point for calculating carbon emissions in this paper is from the separation and thickening of the sludge from the secondary sedimentation tank of the wastewater treatment system to its final output as a product or energy recovery. In order to accurately compare the carbon emissions in different sludge treatment routes, 1 t of dry sludge

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[*] Corresponding author: Li_jj2@hdec.com

(DS) is taken as the accounting object, and the calculation is divided into direct carbon emissions, indirect carbon emissions and carbon offsets according to different emission types.

Direct carbon emissions refer to greenhouse gas emissions occurring within the boundary[3], including combustion from stationary and mobile sources. Indirect carbon emissions are consumption caused by activities within the boundaries of the organization, but GHG emissions occur outside the boundaries, e.g. electricity in the process from the national grid, thermal energy consumed by drying and chemicals added for sludge dewatering. Carbon offsetting means that by recycling resources in sludge, the use of fossil-based energy can be reduced elsewhere, thus reducing total carbon emissions, such as recovering heat generated from sludge incineration for electricity generation, and replacing cement raw materials with residual ash for building materials. The carbon emission accounting boundary and the analysis of carbon emission sources of each process unit are shown in Figure 1.

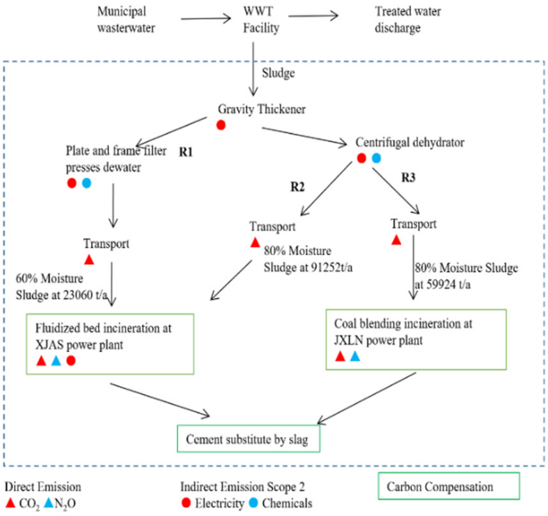

Fig. 1. Carbon emission accounting boundary and source analysis

2.2 Direct Carbon Emission Accounting

In addition to CO_2, greenhouse gases such as CH_4, N_2O, HFCs, PCFs and SF are also included in the assessment of carbon emissions. The impact of different gases on climate change varies according to their life cycle and radiative efficiency. In order to compare the impacts of the various GHGs on the same basis, the Global warming potential (GWP) is multiplied by the GHG emissions to give a uniform conversion to CO_2 equivalent, which characterizes the relative contribution to climate change. GWP in this paper uses the value given by IPCC Fifth Assessment Report[4].The GWP of the greenhouse gases (CO_2, CH_4 and N_2O) involved in sludge treatment and disposal at the 100 years is shown in Table 1.

Table 1. GWP of greenhouse gases

Type of greenhouse gases	CO_2	CH_4	N_2O
GWP	1	28	265

2.2.1 Transporting

The transfer of sludge inevitably requires vehicle transport, which generates direct CO2 emissions due to the combustion of fossil fuels. Most of the large load trucks are diesel vehicles. Diesel consumption is estimated in terms of transport distance. In this paper, the transport distance is taken as 57 km from WWTP to XinJiaAiSi (XJAS) power plant and 38km from WWTP to JiaXinLvNeng(JXLN) power plant, and the fuel consumption of a domestic truck with a capacity of 15 t is about 15 L diesel per 100 km.

$$\mathrm{RL} = \frac{m}{(1-w)M} \times L \times AVG \times \rho_1 \tag{1}$$

In which, RL is the diesel consumption mass, kg; m is sludge dry mass, t; w is sludge moisture content,%; M is unit load capacity, t; L is transport distance, km; AVG is fuel consumption per 100km, L/(100km)； ρ_1 is diesel density, 0.84 kg/L. Hence, the direct carbon emission is given by:

$$\mathrm{E}_{\mathrm{CO_2,transport}} = \mathrm{RL} \times \mathrm{RZ} \times \mathrm{C} \times \alpha \times \frac{44}{12} \times 10^{-3} \tag{2}$$

In which, $\mathrm{E}_{\mathrm{CO_2,transport}}$ is the direct carbon emission of transport (calculated as CO_2), kg; RZ is calorific value of diesel, 43.33 GJ/t; C is carbon content per calorific value of diesel(calculated as C)，20.2 t/TJ；α is carbon oxidation rates of diesel, 98%; 44/12 is ratio of relative molecular masses of CO_2 versus C.

2.2.2 Incineration

Dried sludge with organic matter content above 35% can maintained self-sustaining combustion. The organic carbon of sludge in this study is 39~45% while carbon percentage in dried matter is 20%. CH_4 is the result of incomplete combustion but it is assumed complete combustion in this study as the percentage of sludge added to the incineration is below 30% in either XJAS or JXLN. Hence, CH_4 related carbon emission is not considered in this study. N_2O was calculated using IPCC factors.

$$\mathrm{E}_{\mathrm{CO_2,incineration}} = m \times \mathrm{CF} \times \mathrm{FCF} \times \mathrm{OF} \times \frac{44}{12} \times 10^{3} \tag{3}$$

In which, $\mathrm{E}_{\mathrm{CO_2,incineration}}$ is the CO_2 emission of sludge incineration, kg; CF is carbon percentage in dried sludge as mesured, 20%; FCF is the percentage of fossil carbon in total carbon,12%[5];OF is oxidation factor, 100%[6].

$$\mathrm{E}_{\mathrm{N_2O,incineration}} = m \times \mathrm{EF}_{\mathrm{N_2O,incineration}} \times G_{\mathrm{N_2O}} \tag{4}$$

In which, $\mathrm{E}_{\mathrm{N_2O,incineration}}$ is the N_2O emission of sludge incineration, kg; $\mathrm{EF}_{\mathrm{N_2O,incineration}}$ is the N_2O emission factor of sludge incineration (calculated as N_2O/DS), 0.99 kg/t; $G_{\mathrm{N_2O}}$ is Global warming potential of N_2O, 265.

2.3 Indirect Carbon Emission Accounting

The calculation of indirect emissions generally uses the emission factor method in which carbon mission is calculated by multiple activity data by emission factor.

$$E = D \times EF \tag{5}$$

In which, E is carbon mission, kg; D is the amount of electricity or reagent consumed. The heat consumption is not considered in this study. EF is emission factors which are experience derived factors specifying the amount of a CO_2 generated per unit amount of an activity. Detailed EF is shown in table 2.

Table 2. Indirect carbon emission factors

D	EF	Reference
Electricity	0.5839 kg CO_2/kWh	[7]
PAM	25 kg CO_2/kg	[8]
$FeCl_3$	8.3 kg CO_2/kg	[8]
CaO	1.4 kg CO_2/kg	[8]

The main energy consumption required for all equipment such as sludge pumping and dehydration are electricity. Electricity related CO_2 emission is also calculated by EF method. The energy structure in different regions is different, so with the electricity emission factors. In this paper, national electricity average EF value of 0.5839 kg/kWh published by Ministry of Ecology and Environment is used. The sludge treatment process requires the addition of dewatering chemicals, mainly $FeCl_3$, CaO and polyacrylamide (PAM). The dosage of inorganic coagulants is usually 5% to 20% of the dry weight of the sludge. Organic flocculants are usually used at a dosage of 0.1% to 0.5% of the dry weight of the sludge. The specific energy consumption of plate and frame filter presses, belt filter presses and centrifugal dehydrator is 15 to 40 kWh/tDS, 5 to 20 kWh/tDS and 30 to 60 kWh/tDS respectively.[9] In this study, the chemical dosage and specific energy consumption data used were from WWTP daily operation and show in table 3 which are comparable with figures in the national guideline and other references. [8-10]

Table 3. Energy and reagent consumptions of process units

Units	Items	Parameters	Remarks	Origin
Gravity Thickener	Electricity	13 kWh/(tDS)	to water content 97%	*
Plate and frame filter presses	Electricity	46.2 kWh/(tDS)	to water content 60%	*
	CaO	254 kg/(tDS)		*
	$FeCl_3$	164 kg/(tDS)		*
Centrifugal dehydrator	Electricity	23.6 kWh/(tDS)	to water content 80%	*
	PAM	4.8 kg/(tDS)		*
Fluidized bed incineration	Electricity	300 kWh/(tDS)	at XJAS, 57km in distance	[9]
Coal blending incineration	Electricity	150 kWh/(tDS)	At JXLN,38km in distance	[11]

* Origin from operation data of WWTP in Jiaxing

2.4 Carbon Offsetting

2.4.1 Energy recovery from incineration

The incineration facilities in this study are equipped with energy recovery equipment to generate electricity and heat. Hence,

$$\mathrm{R}_{incineration} = m \times CH \times EF_{electricity} \tag{6}$$

In which, $\mathrm{R}_{incineration}$ is the carbon offsetting from the combined heat and power generation of incineration; CH cogeneration efficiency of combined heat and power generation, 2467 kWh/t； $EF_{electricity}$ is the emission factors of electricity, 0.5839 kg CO_2/kWh.

2.4.2 Building material substitute by slag

Slag is solid waste from incineration whose main ingredients are heavy metals or SiO_2、Al_2O_3 and Fe_2O_3. Composition of slag is similar to that of silicate cement. It is assumed that organic matter of sludge decomposed thoroughly during calcination and slag used as cement. Hence,

$$\mathrm{R}_{cement\ substitute} = m \times \varphi_2 \times EF_{cement} \tag{7}$$

In which, $\mathrm{R}_{cement\ substitute}$ is the carbon offsetting from silicate cement substitute by slag, kg; φ_2 is the slag production rate, 17.5%[12]; EF_{cement} is the emission factors of silicate cement,0.97 CO_2 kg/kg[13].

3 Results and Discussions

3.1 Carbon Emission Comparisons among Routes

In the wastewater treatment process, a substantial amount of sludge is generated and pumped into gravity thickener at 40000 tDS/a before undergo varied treatment route as shown in figure 1. The distribution of dry sludge among R1, R2 and R3 are 23.3%、46.3% and 30.4%. Detailed calculation of each route is done and illustrated in figure 2.

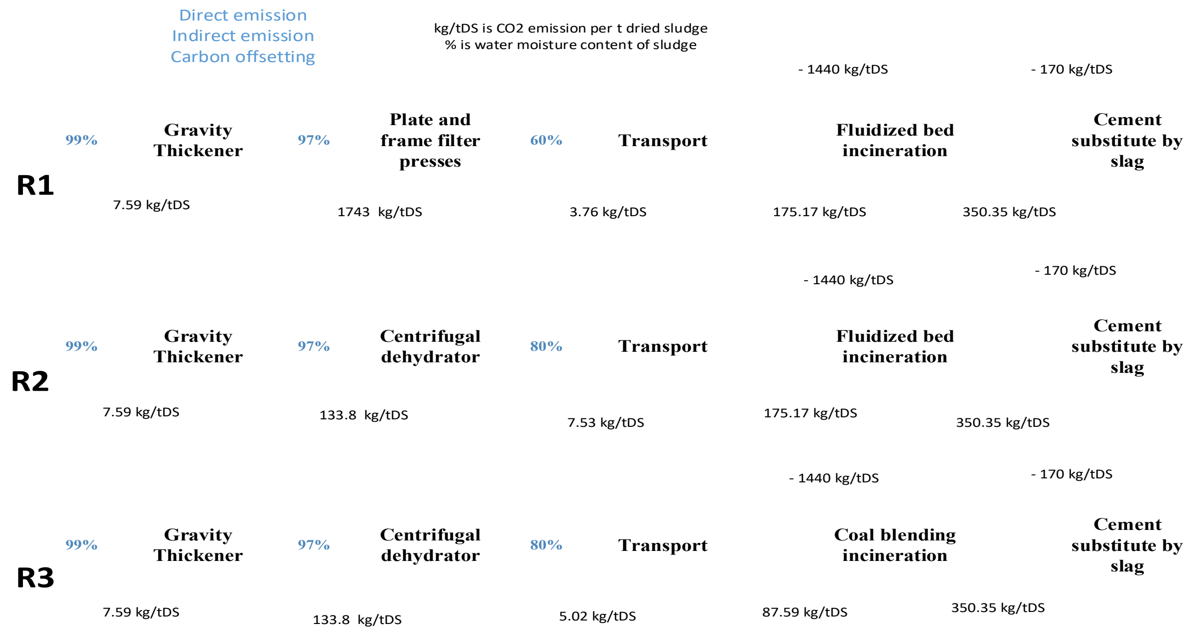

Fig. 2. Carbon emission of R1、R2、R3 route

As shown in table 4, the net carbon emission in R1 is 669.87 $kgCO_2/tDS$. The highest carbon emission occur in the dewatering unit in which indirect emission from the use of $FeCl_3$ and CaO is estimated to be 1361.2 $kgCO_2/tDS$ and 355.6 $kgCO_2/tDS$. Electricity related indirect emission from plate and frame filter press is 26.9 $kgCO_2/tDS$ which is higher than that of pump in gravity thickener at 7.59 $kgCO_2/tDS$. The carbon offsetting occur in incineration from combined heat and power generation (CHP,-1440 $kgCO_2/tDS$) and cement substitute by slag(-170 $kgCO_2/tDS$).However, R1 is most unfavorable in terms of net emission due to the excessive use of chemical agents to reduce water content.

Table 4. Types of carbon emissions, kgCO2/tDS

Routs	Direct emission	Indirect emission	Carbon offsetting	Net emission
R1	354.11	1925.76	-1610	669.87
R2	357.88	316.56	-1610	-935.56
R3	355.37	228.98	-1610	-1025.65
Sum	356.24	664.88	-1610	-588.88

The net carbon emission in R2 is -935.56 $kgCO_2/tDS$. The dewatering unit related emission (133.8 $kgCO_2/tDS$) is second to that of incineration unit. The dramatic difference lies in the chemical PAM(120 $kgCO_2/tDS$). Electricity indirect emission from centrifugal is almost half of that of plate and frame filter press and the difference can be derived from sludge dewatering from 80% to 60%. Therefore, it is evident that increased dewatering rates come at the expense of much higher carbon emissions.

The net carbon emission in R3 is -1025.65. R3 seems to be a moderate improvement to R2. The main difference between two routes is the choice of different incineration equipment with varied electricity consumptions. Besides, transporting to coal blending incineration power plant is nearer with slightly lower delivery emission (5.02 $kgCO_2/tDS$). It is a most promising route for carbon neutral objective. Overall, the net carbon emission with sludge treatment and transport is negative at -588 $kgCO_2/tDS$, however there is still giant room for improvement. A net emission at -1000 $kgCO_2/tDS$ is an achievable task by switching treatment rout from R1 to R3.

3.2 Carbon Mission Comparison among Units

From the generation of sludge within WWTPs, different typical process units with carbon emissions in different routes were analyzed in figure 3.

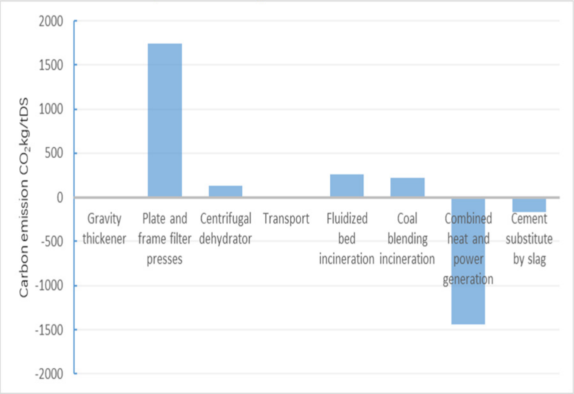

Fig. 3. Carbon emission of R1、R2、R3 route

The emission associated with gravity thickener and transport are negligible. The main carbon emission units of concern are dewatering and incineration. Plate and frame filter press carbon emission is sky high at 1743 $kgCO_2/tDS$ due to chemical consumptions rather than electricity as the indirect emission source. The key focus of future work would be the optimization of dewatering processes to reduce the dosage of chemicals and to develop efficient and low-consumption dewatering reagents.

Considering only 23.3% of sludge was dewatered by plate and frame filter press, it is also advisable of replacement with centrifugal dehydrator.

Incineration related direct and indirect carbon emission is moderate at 218.97 to 262.76 kgCO$_2$/tDS. Thanks to combined heat and power generation of -1440 kgCO$_2$/tDS, both incineration pathways can achieve carbon reduction. Also the cement substitute by slag in this case can contribute to carbon offsetting considerably at -170 kgCO$_2$/tDS. The room for future improvement at power plant would be incinerator improvement to achieve complete combustion and flue gas carbon capture and utilization.

4 Conclusions

The current status of sludge treatments overall is net carbon negatives at -588 kgCO$_2$/tDS. Despite only 22.3% of sludge is treated in R1, overall carbon emission reduction performance is greatly hampered. The total carbon emissions from the three sludge treatment and disposal routes are R3 ＜ R2＜ R1, where R3 (gravity thickening + centrifugal dehydrator + transport + coal blending incineration with combined heart and power generation + cement substitute by slag) is the most low-carbon sludge treatment route, with emissions of -1025.65 kgCO$_2$/tDS.

The main process with carbon emission are dewatering and incineration. From the operator of WWTP level, it is suggested a sustainable management program should be implemented and more works are essential in the fields of sludge treatment process optimization such as reducing or surrogating chemical reagents with low carbon footage, mechanical dewatering substitution by bioheat dewatering alternative, and explore noval carbon offsetting pathways.

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