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Sludge treatment and resource recovery towards carbon neutrality in China: current status and future perspective

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ABSTRACT

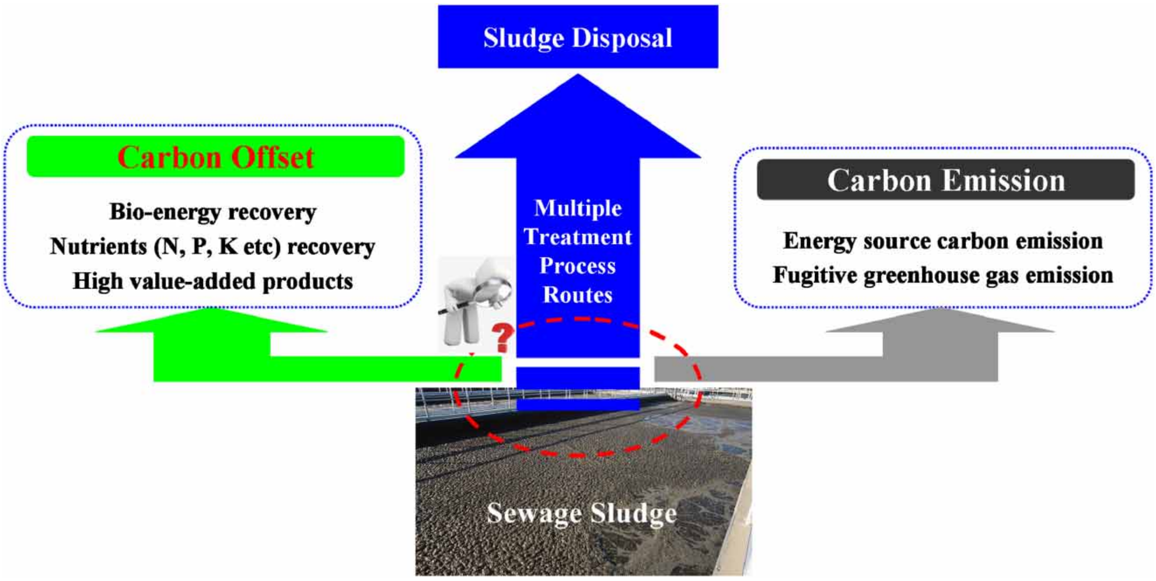
Global warming – mainly caused by carbon emissions – is a major global challenge for human sustainable development. Carbon emission reduction and resource recovery from sludge treatment are critical to the carbon neutralisation of future wastewater treatment plants. This paper analyses the key elements of carbon emissions during sludge treatment and disposal, namely energy source carbon emissions, fugitive carbon emissions and carbon compensation. Of the four mainstream process routes analysed in this work, anaerobic digestion + dry incineration is identified as the route with the highest potential for reducing carbon emissions in the future. Finally, based on a review of current international research hotspots, the future development directions for sludge treatment and resource recovery are discussed. This paper thus provides a comprehensive understanding of the current sludge treatment processing routes and serves as a reference for process route selection and future research on carbon neutralisation.

Key words: carbon emissions, energy balance analysis, mainstream process routes, sewage sludge, sludge disposal

HIGHLIGHTS

- The key elements of carbon emissions during sludge treatment are analysed.
- Four mainstream process routes of sludge treatment from the perspective of carbon neutralisation are analyzed.
- The route with the highest potential for reducing carbon emissions is proposed.
- Current international research hotspots of resource recovery from sludge are overviewed.
- Innovative low-carbon technologies for resource recovery are expected.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Global warming is a huge threat to human sustainability. In May 1992, the United Nations Conference on Environment and Development adopted the United Nations Framework Convention on Climate Change. At the United Nations Climate Change Conference in December 2015, 196 parties signed the Paris Agreement, agreeing to the goal of limiting global temperature rise to 2 °C (United Nations 2018). In September 2020, China announced that it aims to achieve its carbon peak by 2030 and its carbon neutrality by 2060. In addition to combating global warming, these goals are crucial for China to improve its environmental quality.

China is currently the largest carbon-emitting country in the world, accounting for more than 25% of the global emissions (IEA 2017; Zhou *et al.* 2019), and carbon emissions from sewage treatment account for 1–2% of total emissions in any society (Wang 2017; EPA, 2019; Dai *et al.* 2021). Although sewage treatment produces little carbon emission, it is an energy-intensive industry with major social and environmental impacts. Extracting carbon, nitrogen and phosphorus from wastewater could generate resources and conserve energy, both of which can help offset the carbon emissions (Li *et al.* 2015). In addition, sewage treatment is a key area for reducing carbon emissions in developed countries (Wang 2017), and the related findings and best practices can be transferred to China as well. The volume of urban sewage treatment in China now exceeds 200 million m^3/day (the largest in the world), and the resulting sludge volume, estimated at 80% moisture content, exceeds 65 million tons annually (Geng *et al.* 2020). Sludge is a by-product of sewage treatment that contains perishable organic matter, pollutants and nutrients, giving it the dual attributes of a pollutant and a resource (Xu *et al.* 2020). Sludge is a complex multimedia system with high water content, micron-sized inorganic particles and supramolecular organic matter with unknown structure (Xu *et al.* 2021a). Sludge treatment has a high potential to reduce carbon emissions, but its efficiency is low. To improve the efficiency of sludge treatment processes, vast amounts of chemicals and energy need to be used, which increase greenhouse gas emissions. Thus, reducing carbon emissions during sludge treatment and disposal is critical for achieving carbon neutrality of the sewage treatment.

In this paper, the current routes of sludge treatment and disposal are analysed from the perspective of carbon neutralisation, and the selection basis for sludge treatment and disposal are determined. The future development directions for sludge treatment and resource recovery are also provided. This paper provides a comprehensive understanding of the current routes of sludge treatment and serves as a guide for future research on carbon neutralisation.

2. KEY ELEMENTS OF CARBON EMISSIONS ACCOUNTING

The organic matter in sludge from a wastewater treatment plant mainly comes from organic matter adsorbed from wastewater, microbial cells and extracellular polymeric substances. During sludge treatment and disposal, organic matter decomposes and transforms into CO_2. This CO_2 is part of the natural carbon cycle and will not cause net CO_2 increase in the atmosphere, according to the Intergovernmental Panel on Climate Change (IPCC 2006).

Figure 1 categorises carbon emissions that arise during sludge treatment and disposal into three types: energy source carbon emissions, fugitive carbon emissions and carbon offset. Energy source carbon emission refers to the carbon emissions caused by the consumption of primary energy (e.g., coal, natural gas), secondary energy (e.g., electricity, diesel) and chemicals. Fugitive carbon emission refers to fugitive CH_4, N_2O and other greenhouse gases. According to the IPCC, 1 t CH_4 and 1 t N_2O over a period of 100 years have the same global warming capacity as 21 t CO_2 and 310 t CO_2, respectively (IPCC 2006). Carbon offset refers to the recycling of bioenergy (CH_4 and H_2) or resources (N, P and K) in sludge to replace fossil energy and chemicals, thus reducing greenhouse gas emissions.

3. ANALYSIS OF CARBON EMISSIONS IN MAINSTREAM SLUDGE TREATMENT AND DISPOSAL PROCESSES IN CHINA

With the recent focus on sludge treatment and disposal in China, four mainstream technical routes have emerged (Geng *et al.* 2020): (1) anaerobic digestion (AD) + land use; (2) aerobic composting + land use; (3) dry incineration + ash landfill or utilisation as building material; (4) deep dewatering + emergency landfill. Sludge treatment and disposal processes have conventionally been chosen on the basis of their technical and financial feasibility

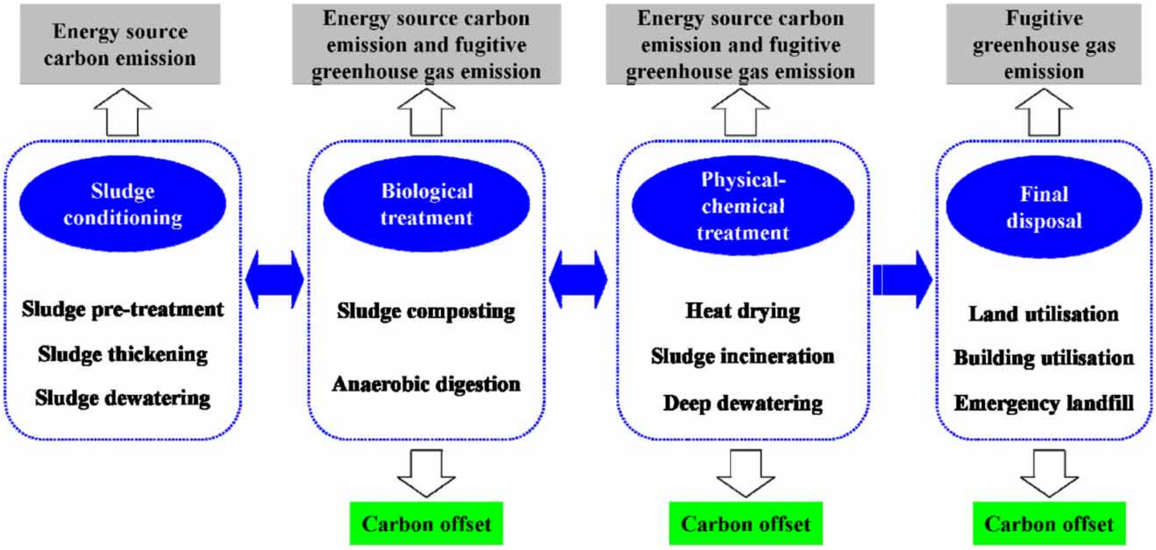


Figure 1 | Key elements of carbon emission during sludge treatment and disposal.

(Yang *et al.* 2015). With the future goals of carbon peak and carbon neutralisation, carbon emission will become an important indicator in selecting sludge treatment and disposal process routes.

Sludge treatment and disposal systems are complex, with numerous potential process routes. Table 1 summarises the carbon emission analyses for four typical process routes, with a focus on their differences.

Table 1 | Carbon emission analyses for four typical process routes

	Carbon emission			
Process routes	**Energy source carbon emission**	**Fugitive carbon emission**	**Carbon offset**	**Level**
AD + land use	CH_4, N_2O	EC, FC, CRC	Biogas replaces fossil energy; organic fertiliser replaces chemical fertiliser	Extremely low
AC + land use	CH_4, N_2O	EC, FC, CRC	Organic fertiliser replaces chemical fertiliser	Low
Dry incineration + utilisation as building material	CH_4, N_2O	AFC, EC, FC	Bioenergy replaces traditional heat energy; byproducts replace building raw materials	Medium
Deep dewatering + emergency landfill	CH_4, N_2O	EC, FC, CRC	Landfill gas as an alternative to fossil energy	High

AD, anaerobic digestion; AC, aerobic composting; EC, electricity consumption; FC, fuel consumption; CRC, chemical reagent consumption; AFC, auxiliary fuel consumption.

3.1. Process route of AD + land use

AD – the world's standard sludge stabilisation technology – can stabilise perishable organic matter, reduce pathogens, minimise sludge volume and recover bioenergy (Xu *et al.* 2020). Sludge is a rich source of nutrients, such as carbon, nitrogen, phosphorus and potassium. Sludge can be used to improve soil properties and recycle nutrients. The route of AD + land use is also recommended in the Technical Guide for Sludge Treatment and Disposal of Urban WWTPs.

The consumption of heating energy, stirring energy, dewatering agent and land-use power generates energy source carbon emissions, as indicated in Table 1. AD-based biogas and landfill-based CH_4 and N_2O trigger the emission of fugitive greenhouse gases. AD-based biogas can replace fossil fuels to compensate for carbon emissions and reduce greenhouse gas emissions. The digestate can be used to replace nitrogen and phosphorus fertilisers, further compensating for carbon emissions. Following the carbon emission accounting method specified by IPCC (2006), the route of AD + land use yields negative carbon emissions, a finding also reported by previous studies (Yang *et al.* 2015; Geng *et al.* 2020; Cossel *et al.* 2021). To reduce carbon emissions, increasing AD efficiency (bioenergy recovery), using advanced AD technology (to reduce system energy consumption), substituting green chemicals in digestate dewatering and recovering nitrogen and phosphorus from the fermented liquid are the mainstream directions in the route of AD + land use. Based on the outcomes of engineering practices, the authors suggest that AD be carried out in WWTPs to facilitate resource recycling and the on-site treatment of fermented liquid generated by AD.

3.2. Process route of aerobic composting + land use

Sludge can be composted aerobically because it is rich in perishable organic matter; on aerobic composting, this perishable organic matter undergoes degradation and stabilisation; however, some heavy metals and organic pollutants may not be removed or degraded. If the concentrations of heavy metals and pollutants in the products of aerobic composting exceed the standards of land use, the products cannot be used for landscaping, soil remediation and agriculture or as a growing medium.

The consumption of chemicals and energy during sludge dewatering, transportation of auxiliary materials, oxygen delivery and waste gas treatment during the composting process, as well as energy consumption during land use increases energy source carbon emissions. Moreover, CH_4 and N_2O released from the route of aerobic composting + land use cause fugitive greenhouse gas emissions; nevertheless, using nitrogen and phosphorus fertilisers instead of conventional fertilisers can help compensate for these emissions. Generally, the route of aerobic composting + land use is a low-carbon emission process. To further reduce carbon emissions, the focus should be on improving smart controls of the aerobic composting process, reducing energy and agent consumption during odour treatment, reducing the use of auxiliary materials and developing efficient sludge resource utilisation technologies.

3.3. Process route of dry incineration + ash landfill or utilisation as a building material

Sludge drying-incineration is an effective treatment and disposal method when the feasibility of the land use of sludge is low. The organic matter in sludge can be recycled by drying and incineration. Moreover, sludge volume can be reduced by mineralising its organic matter. In many areas of China, sludge has low organic content (usually VS $< 55\%$ of TS), and the inorganic components are mostly fine sand (Xu *et al.* 2021b); therefore, the incineration ash can be used as a building material.

As shown in Table 1, energy source carbon emissions are mainly due to the consumption of chemicals and energy during sludge dewatering, drying and incineration. Dry incineration also emits CH_4 and N_2O, which triggered fugitive greenhouse gas emissions. However, the energy recovered from the incineration process for drying can compensate for the carbon emissions. This process route emits medium levels of carbon. To further reduce carbon emissions, the focus should be on developing efficient deep dewatering technologies, reducing the energy consumption of sludge drying, improving process rationality and enhancing the overall smart integration level.

3.4. Process route of deep dewatering + emergency landfill

Deep dewatering + emergency landfill has long been a popular sludge treatment and disposal method in China. This method of transitional treatment and disposal occupies land, wastes resources, and may cause secondary pollution.

As shown in Table 1, deep dewatering of sludge requires substantial amounts of dewatering agents and energy. Moreover, because sewage sludge is rich in water and organic matter, landfill of sludge does not only realise the resource utilisation of organic matter but also causes the disorderly release of a large number of greenhouse gases such as CH_4 and N_2O, thereby increasing carbon emissions. The route of deep dewatering + emergency landfill is a high-carbon emission process. Although an emergency landfill is a low-cost way from an economic point of view, to reduce carbon emission, this process route will be gradually abandoned in the future, and it just is an emergency treatment method at a certain stage.

3.5. Comparative analyses of carbon emissions in different process routes

As shown in Figure 2, carbon emissions from AD + land use are the lowest, followed by aerobic composting + land use, whereas deep dewatering + emergency landfill has the highest carbon emission levels. Figure 2 also reveals that the higher the organic matter content of sludge, the lower the carbon emission from AD + land use and dry incineration + ash landfill. For example, compared with 40% organic sludge, 70% organic sludge

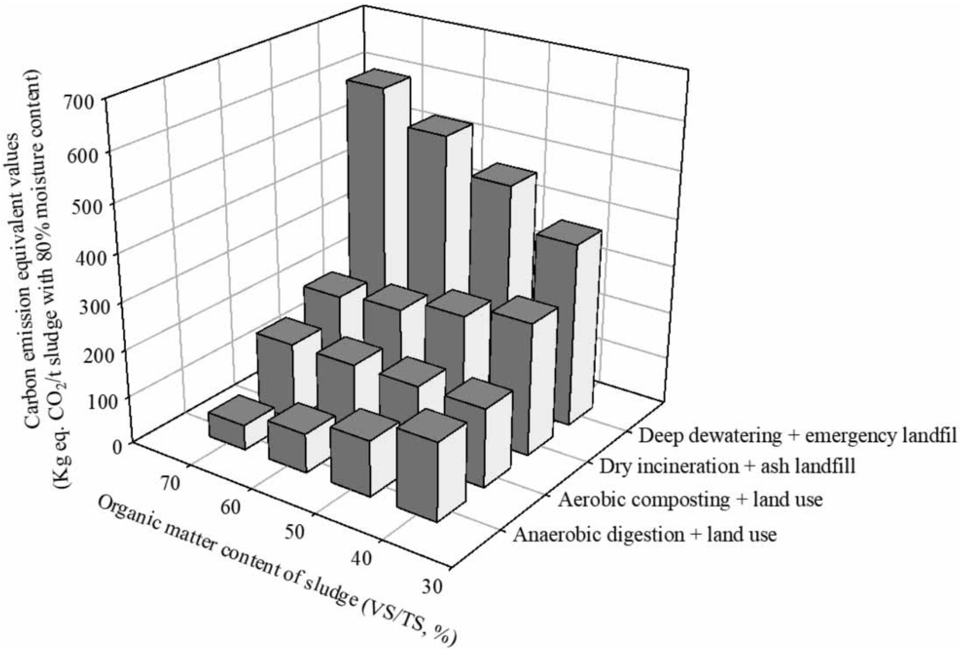


Figure 2 | Carbon emission equivalent values of sludge with various organic matter content and process routes: calculations are based on the accounting methods specified in the IPCC guidelines (IPCC 2006) (VS, volatile solid; TS, total solid).

reduces carbon emissions from AD + land use by 67.9% and dry incineration + ash landfill by 23.9%. Aerobic composting + land use has no significant effect on carbon emissions. However, the greater the organic matter content of sludge, the higher the carbon emission from deep dewatering + emergency landfill (Figure 2). Hence, from the perspective of reducing carbon emissions, the route of AD + dry incineration + ash landfill or utilisation as a building material may have the highest development potential for sludge resource recovery, treatment and final disposal.

4. DEVELOPMENT DIRECTIONS FOR SLUDGE TREATMENT AND DISPOSAL

To achieve carbon neutrality in sludge treatment and disposal, the focus should be on energy efficiency, consumption reduction and resource recovery. Currently, only 5% of all WWTPs in China use AD technology for sludge treatment, compared with >50% in developed countries (Xu *et al.* 2021b). To achieve efficient sludge reduction and bioenergy recovery, advanced AD technologies (high-solid AD with thermal hydrolysis and anaerobic co-digestion of sludge and other organic wastes) should be widely promoted and implemented. Smart controls in drying and dewatering equipment in deep sludge dewatering should be improved, and environment-friendly dewatering agents and high-efficiency dewatering technology should be developed. For the end treatment of sludge, dry incineration can be coupled with AD technology to minimise the overall energy consumption of the system.

In addition, China's 2020 Implementation Plan for Strengthening Shortcomings for Urban Domestic Wastewater Treatment Facilities, issued by the Ministry of Housing and Urban–Rural Development and the National Development and Reform Commission (2012), encourages the use of biomass utilisation + terminal incineration for sludge disposal. AD technology is a part of 'biomass utilisation', so the route of AD + dry incineration is consistent with the aforementioned policy for sludge treatment and disposal. As shown in Table 2, the route of AD + dry incineration consumes less energy than dry incineration. For example, with 100 t sludge (80% moisture content; 50% organic content), the additional energy required for independent sludge incineration is 25,142 kW·h, whereas the energy generated by the route of AD + dry incineration is 1,004 kW·h, and the energy generated by the route of advanced AD + dry incineration can increases from 1,004 kW·h to 7,889 kW·h. AD recovers bioenergy from sludge, improves the dewatering performance of sludge and reduces drying energy consumption. Thus, the sum of bioenergy recovered and energy saved in the drying system exceeds the energy lost during AD. Although AD extends the duration of the sludge treatment process, it helps to reduce carbon emissions.

Table 2 | Energy balance analyses of the process routes of dry incineration, AD + dry incineration, and advanced AD + dry incineration

Parameters	**Dry incineration**			**AD + dry incineration**			**Advanced AD + dry incineration**			**Equations**
Organic matter content (VS, %)	50	60	70	50	60	70	50	60	70	
Energy consumption of thermal hydrolysis (kW·h)	–	–	–	–	–	–	13,260	13,260	13,260	Equation (1)
Heating energy consumption of AD (kW·h)	–	–	–	10,296	10,296	10,296	–	–	–	Equation (2)
Organic matter degradation rate of AD (VS_{re}, %)	–	–	–	40	45	50	50	55	60	
Energy generated by biogas from AD (kW·h)	–	–	–	20,937	28,265	36,639	27,710	36,578	49,140	Equation (3)
Moisture content of digestate after dewatering (%)	–	–	–	70	72	75	65	68	70	
Energy consumption of digestate dewatering (kW·h)	–	–	–	960	876	780	900	804	696	Equation (4)
Energy consumption of drying (kW·h)	64,286	64,286	64,286	27,429	28,157	30,086	19,286	20,459	19,886	Equation (5)
Energy generated by incineration (kW·h)	39,144	51,707	64,269	18,751	24,181	28,587	13,624	18,062	21,452	Equation (6)
Energy output (kW·h)	−25,142	−12,579	−16	1,004	13,116	24,065	7,889	20,117	36,750	Equation (7)

Equation (1): $E_1 = Q_1(100 - T_1)\mathrm{k}_1$

Equation (2): $E_2 = Q_2(37 - T_1)\mathrm{k}_1 \times 1.1$

Equation (3): $E_3 = 100 \times (1 - 0.8)\mathrm{VS} \times \mathrm{VS}_{\mathrm{re}} \times \mathrm{Y} \times \mathrm{CV}_{\mathrm{CH}_4} \times \mathrm{k}_2$

Equation (4): $E_4 = \mathrm{DS} \times \mathrm{W}$

Equation (5): $E_5 = (m_1 - m_2)\mathrm{k}_3$

Equation (6): $E_6 = E_{\mathrm{G}} - E_{\mathrm{EG}}$

Equation (7): $\Delta E = E_3 - E_1 - E_2 + E_4 - E_5 + E_6$

The calculation is based on 100 t of sludge with 80% water content; Q_1 is the mass of hydrolytic sludge (feeding sludge with 85% water content); T_1 is the initial temperature of sludge (15 °C); k_1 is the heat consumed by heating 1 unit of water at 1 °C, kW·h; Q_2 is the mass of AD (feeding sludge with 95% water content); Y is the methane yield, 0.85 m^3/kg VS_{re} from AD and 0.90 m^3/kg VS_{re} from advanced AD; CV_{CH4} is the methane calorific value, 35.9 MJ/m^3; k_2 is the utilisation efficiency of biogas, 0.95; DS is the mass of sludge dry basis, t; W is the energy consumption of sludge dewatering, calculated by 60 kW·h/t DS; m_1 is the water content of dewatered sludge, t; m_2 is the water content of dried sludge, t; k_3 is the heat consumed by evaporating 1 m^3 water in the drying process, calculated by 900 kW·h/t water; E_G is the heat of gas generated during incineration, kW·h; E_{EG} is the heat of exhaust gas, kW·h. AD, anaerobic digestion; VS, volatile solid.

Furthermore, the reduction of sludge in AD reduces the investment costs for subsequent dry incineration facilities. From the perspective of carbon emission reduction and cost savings, AD + dry incineration has a better development potential than dry incineration of sludge alone. Achieving high-efficiency low-grade heat source utilisation (such as sludge dewatering and drying technology based on low-grade heat source) will further improve the advantages of this approach.

The efficient energy recovery and material recycling of sludge has become an international research hotspot in light of the global response to climate change and energy shortage. Table 3 lists 17 popular keywords on sludge energy and resource recovery that are vital for maximising sludge resource utilisation. Pursuing interdisciplinary and advanced research should improve the technical level of sludge treatment and disposal, as well as the level of energy and resource recovery from sludge. The innovative low-carbon technologies, which aim to minimise carbon emission from sludge treatment and maximise sludge resource recovery, are expected to be developed. For instance, develop a new method or biochemical reactor that can convert CO_2 to bioenergy in the biochemical treatment of sludge, which can improve the conversion efficiency of bioenergy and reduce the emission of CO_2 at the same time. We have carried out some preliminary relevant researches in the laboratory (Xu *et al.* 2020; Xu & Dai 2021a, 2021b).

Table 3 | International research hotspots relating to the recovery of energy and resources from sludge

	Target production	**Description**	**References**
Energy recovery	CH_4	1 kg COD theoretically produces 0.35 m^3 CH_4 (approximately 12,530 kJ/g COD)	Daigger (2009)
	H_2	Maximum production can reach 0.27 L H_2/g COD	Koskinen *et al.* (2008)
	MFC	1 kg COD theoretically produces 4 kWh by MFC	Halim *et al.* (2012)
	Heat energy	Dry sludge can produce heat due to the high calorific value of sludge (12 MJ/kg)	Zhao *et al.* (2010)
	Biodiesel	Biodiesel produced from sludge can satisfy 1% of the biodiesel demand	Dufreche *et al.* (2007)
Resource recovery	Fatty acids	VFAs can serve as the internal carbon source for removing N and P	Li *et al.* (2011)
	PHA	PHA (biodegradable plastics) production rate can be 0.59 g/gCOD	Takabatake *et al.* (2002); Yan *et al.* (2006)
	Protein	Protein recovery rate can be as high as 80%	Hwang *et al.* (2008)
	Lactic acid	Lactic acid concentration produced from sludge can be 73 g/L	Marques *et al.* (2008)
	Phytohormone	Auxin content in sludge compost can be 3.80 mg/kg	Tomati *et al.* (1988)
	N recovery	N content in sludge is 3–4% and can satisfy 30% of the demand for N fertiliser	Kalogo & Monteith (2008)
	P recovery	P content in sludge is 2–3% and can satisfy 50% of the demand for P fertiliser	Chen *et al.* (2019); Wilfert *et al.* (2016)
	Metal	Au and Ag content in sludge incineration ash can be 2 g/kg	Mulchandani & Westerhoff (2016); Geng *et al.* (2020)
	Biochar	Biochar produced from sludge can be used as soil conditioner	Woolf *et al.* (2010)
	Organic fertiliser	Stabilised sludge can be used as organic fertiliser due to the presence of nutrients (N, P, K) and microelements	Sharma (2017)
	Functional materials	Sludge can be used to produce functional materials due to the high content of C, Si and metal	Yuan & Dai (2015)
	Building materials	Incineration ash can be used to replace 5–20% of cement raw material	Yen *et al.* (2011)

COD, chemical oxygen demand; MFC, microbial fuel cell; VFAs, volatile fatty acids; PHA, polyhydroxyalkanoates.

5. CONCLUSIONS

Sewage sludge is a multimedia and multi-component complex system, which is rich in resource substances and a certain amount of pollutants, resulting in its dual attributes of ‘pollution’ and ‘resources’. Sludge treatment can not only cause energy source carbon emission and fugitive carbon emission but also realise carbon offset through resource recovery. Therefore, reducing energy source carbon emission and fugitive carbon emission and improving carbon compensation are important research directions in the future sludge treatment process. Considering operability and economic cost, over 60% of sludge currently makes it to landfills, whereas AD treatment accounts for only 5% of sludge treatment; hence, AD should be promoted for sludge treatment. If AD-based digestate cannot be used for land use, the carbon emission and energy balance analyses suggest that the route of AD + dry incineration for sludge treatment is the most promising route for reducing carbon emissions. Therefore, the incineration should also be improved to avoid the generation of toxic and harmful gases. Moreover, efficient resource recovery from sludge has become a hot spot in international research of sewage treatment because sewage sludge is rich in organic matter and nutrients. Innovative low-carbon technologies must be developed to fully utilise sludge resources and reduce carbon emissions.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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