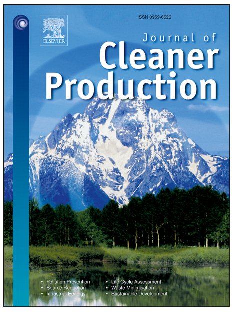


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# Hybrid environmental and economic assessment of four approaches recovering energy from sludge with variant organic contents

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**Abstract:** Anaerobic digestion (AD), specific incineration (INC), co-incineration in coal-fired power plants (CINP) and co-incineration in cement kilns (CINC) are the four common approaches recovering energy from sludge in South China, where low-organic-content sludge is an important issue influencing the performance of the four approaches. In this study, the four approaches are assessed from the aspects of environmental impacts, energy efficiency and economic performance (3E), and the influence of sludge organic content on the results is particularly paid attention to. When sludge organic content decreases from 70% to 40%, the total environmental impacts of the four approaches change slightly by 1.6–7.1%, but their energy efficiencies decreases by 43–66% and their net present values decrease 24–317% for a project with treatment capability of 100 tons of sludge solids per day. AD has the best energy efficiency and economic performance, but its environmental burden derived from heavy metals spread on land is the heaviest. CINC has the least environment impact, and its energy efficiency and economic performance are both close to

AD. Hence, both AD and CINC are good choices for the treatment of high-organic-content sludge, but CINC show advantage over AD when dealing with low-organic-content sludge. The findings will help guide decisions about sludge handling for existing wastewater treatment plants and those that are still in the planning phase in South China.

**Keywords:** anaerobic digestion; co-incineration; incineration; life cycle assessment; sludge

## 1. Introduction

Sewage sludge is a vital byproduct from wastewater treatment plants (WWTPs) because of its huge quantity and heavy environmental and economic burden derived from energy and materials consumption on treatment and disposal. Sludge utilization is an important step to decrease the negative impact and simultaneously upgrade conventional WWTPs to innovative producers of clean water, energy and resources. It is a known fact that sludge can be converted to compost, building materials, fuels, electricity or heat through different approaches. Among them, technologies recovering energy from sludge have attracted much attention because the energy recovered in different forms can be used widely and more competitive in some cases than those products limited by local conditions or only sold in specialized markets.

Anaerobic digestion, specific incineration, co-incineration in power plants and co-incineration in cement kilns are the four mature technologies, and their cases can be seen worldwide. Owing to functional microbial flora, anaerobic digestion can convert biodegradable organic matter to biogas, in which methane accounts for 50–70% by volume [1]. Biogas can be burned in boilers to generate heat or burned in power generators, and can also be purified to produce pure methane like natural gas [2]. However, anaerobic digestion can only utilize 20–60% of organic content in sludge [1] despite great economic and environmental performance [3]. Special incineration has the advantage of destroying organic substances completely and generating heat or electricity synchronously, but its capital expenditure is commonly high and few cities can afford the facilities, especially in developing states. On the other hand, financially-capable cities often encounter the lack of usable land and the opposition of nearby residents. Co-incineration addresses these weaknesses by treating sludge in existing power plants [4] or cement kilns [5]. This can also decrease the initial capital expenditure. Moreover, dry sludge can replace some coal in power plants or replace some coal and raw materials (clay, silica sand) in cement kilns [5, 6]. Certainly, some supplementary installations are required for co-incineration, such as transportation devices, silos and thermal dryers.

Following consideration of the difference of these technologies, it is important and not easy for decision-makers to choose an optimal one or ones based on local conditions. Life cycle assessment (LCA) is a common method to analyze environmental impacts [7], and it can give the quantitative and overall information on resources consumption and environmental emissions of systems investigated [8]. LCA studies on sludge management have been widely conducted in recent years [9, 10]. In addition to LCA, economic performance is also considered as an indicator to provide an overall view when comparing different alternatives [11]. However, there are often inverse options owing to different regional conditions. For example, according to the report [12], the combination of anaerobic digestion and agricultural land application should be the most environmentally friendly among different routines. On the contrary, owing to possible release of heavy metals to soil, anaerobic digestion followed by land application does not perform better than its combination with incineration [13]. Similarly, co-incineration with coal is sometimes acknowledged to be the most environmentally and economically costly [3], while in other works [5, 14], thermal drying-incineration is preferable to co-combustion and cement production. Therefore, the difference derived from localized conditions should be stressed in LCA.

Among localized parameters, sludge characteristics are the major factor resulting in different assessment results, especially for the approaches from sludge to energy. Sludge energy potential is dependent on its organic content, but the content even varies from 30% to 80%. High organic content of 60–80% is the common situation [1], but low-organic-content sludge is also generated in quantity, especially in WWTPs receiving rainfall or some industrial wastewater in those developing cities without complete pipeline networks [15]. For example, several million tons of low-organic-content sludge dry solids are produced annually in South China. It is necessary to configure treatment facilities reasonably on the basis of sludge characteristics because this factor would determine sludge biogas potential and calorific value, and even alter assessment conclusions. However, the effect of low-organic-content sludge has rarely been considered carefully in previous assessments on sludge-to-energy approaches.

Considering the knowledge gap and the actual demand in South China, the above-mentioned common sludge-to-energy approaches, anaerobic digestion, incineration and co-incineration are assessed together with other necessary auxiliary processes. During the comparative assessment, the influence of variant sludge organic content, especially low-organic-content sludge with VS/TS lower than 60%, is focused on in views of life cycle environmental impact, energy efficiency and economic performance (3E). The average data collected from actual treatment facilities and relevant literatures are utilized to complete the assessment. The findings will extend the existing knowledge and help guide decisions on sludge treatment and utilization for existing or planning

WWTPs in South China.

## 2. Materials and methods

### 2.1 sludge characteristics

In order to set a uniform basis, thickened sludge with TS 5% is used as the feedstock of all the configurations, as gravitational or mechanical concentration is the first step in all the investigated WWTPs. Sludge characteristics are usually steady for a certain WWTP, but vary in a large range across different WWTPs. Based on our survey of dozens of WWTPs (Table S1) and the relevant references [16], the generalized characteristics are shown in Table 1.

Sludge organic content, represented by volatile solids (VS) content in total solids (TS), determines sludge biogas potential and calorific value, and its change would alter many conditions and parameters of sludge treatment processes, for example, electricity and natural gas consumption. Hence, the influence of variant sludge organic content is specially analyzed by setting four types of feed sludge with VS/TS ratios of 40%, 50%, 60% and 70%, respectively. In other words, the four types of sludge are used as the feedstock of all the configurations. In fact, lower VS/TS ratios are also found in some WWTPs, but this kind of 'inorganic' sludge should not be treated as a potential source for energy recovery. This method can specify the influence of sludge organic content and provide valuable information for different WWTPs. The four types of sludge have the same elementary composition, and their calorific values are positively proportional to their organic content. Half of the upper limit values in Chinese regulation "GBT 24600-2009" for land remediation are used as the basic heavy metal contents in sludge solids, but a fluctuation of 30% would be considered combining uncertainty analyses of heavy metals released to soil.

**2.2 System definition**

The functional unit for assessment is defined as 1 ton of dry solid (1 t TS), i.e. 20 tons of thickened sludge containing 1 t TS enter the four systems listed below:

(1) AD: thickened sludge→anaerobic digestion→high-pressure dewatering→land use

(2) INC: thickened sludge→dewatering→thermal drying→incineration→landfill

(3) CINP: thickened sludge→dewatering→thermal drying→co-incineration in coal-fired power plants→landfill

(4) CINC: thickened sludge→dewatering→thermal drying→co-incineration in cement kiln

The flow charts and the outline boundary are illustrated in Fig. 1. It is assumed that all process variants are assessed in operation only and the impacts related to minor consumable materials and the construction of the facilities are not considered because their impacts are negligible in comparison to those in the long operation period [17]. The four configurations consume energy (electricity, natural gas, coal and diesel) and materials (e.g. $FeCl_3$, polymers, $Fe_2O_3$, etc.), which are concluded in Table 2. On site, there would be possible surplus electricity output and pollutants emission, which are also dominated. The generated electricity would replace some grid electricity and the displacement effect is calculated referring to Chinese average grid electricity generation [18]. The wastewater from dewatering and drying is sent back to WWTPs, and only the electricity consumed on transportation (1.05 kWh/t) [19] and treatment cost are considered in the assessment. The detailed information of the four configurations is given as following.

In an AD process, thickened sludge is heated to 35–40 °C before entering the mixed digester tank. After digestion, the digestate is dewatered to a cake and then transported off site for recycling on land. Besides feed sludge, the inputs include chemicals, heat for warming feed sludge and digesters, and electricity for transporting and stirring sludge. The heat consumption is a function of the size of digesters and local weather condition. Thus, a completely-stirred cylindrical digester with sludge retention time (SRT) of 22 days, total volume of 5280 $m^3$ and working volume of 4400 $m^3$ is assumed referring to some small and mediate-size WWTPs. The specific heat capacity of feed sludge is 4.2 kJ/(kg·K) [20] and the heat transfer coefficient of the digester wall is 2.5 kJ/($m^2$·h·K) referring to design specifications [21]. The average ambient temperature is set at 10 °C. Thus, the heat consumed by anaerobic digestion should be 2.8 GJ/t TS. Corresponding to the four VS/TS ratios, the organic removal rates in anaerobic digestion are 20%, 35%, 40% and 50%, respectively, and the biogas yields are 80, 175, 240 and 350 $m^3$/t TS, respectively, referring to the relevant reports [1, 15, 22]. Biogas produced from AD is first scrubbed to remove moisture and $H_2S$. A minute quantity of electricity is used by 0.55–0.75 kW compressors, and a little desulfurizer is consumed (Table 2). Afterwards the biogas is supplied to a combining heat and power (CHP) system, in which 35% of energy in biogas (23 MJ/$m^3$) is converted to electricity and 50% is converted to thermal energy in hot water at 90 °C [23]. The latter is first used to maintain the mesophilic condition of digesters. The possible residual heat is not further utilized in the assessment. During CHP processes, the pollutant emissions include CO of 986 mg/kWh [24], $NO_x$ of 821 mg/kWh [24], $SO_2$ of 439 mg/kWh [24], dust of 164 mg/kWh [25] and non-methane volatile organic carbon (NMVOC) of 136 mg/kWh [26]. On the other hand, if the recovered heat is insufficient for anaerobic digestion itself, natural gas (38.5 MJ/$m^3$) is supplemented with a thermal efficiency of 90%, and the relevant emissions use the limit values in the Chinese regulation “GB 13271-2014” on natural gas boilers. This setting is also used in other scenarios. Digested sludge is mechanically dewatered and then spread in specific land. Sludge water content should be controlled lower than 60% before land use according to the legal requirement in China, and accordingly high-pressure (2–5 MPa) frame filter is often used to dewater sludge with the assistance of inorganic flocculants [27]. In spite of high electrical consumption and high dose of ferric chloride and calcium oxide, this technology needs less capital and operational expenditure than thermal drying [28]. Diesel trucks accomplish the transport of dewatered sludge from WWTPs to a destination, which is empirically assumed to be a distance of 60 km. The relevant atmospheric emissions are obtained from the Chinese regulation GB17691-2005 on exhausted pollutants from vehicles. The setting is also for the other systems. Finally, sludge is used to restore abandoned mines and tunnels, cover municipal waste landfill sites, level construction sites and just heap in no man's land, and only a small quantity of digested sludge is used in agricultural land after further processing in South China. Considering the non-agricultural use, the substitution of chemical fertilizer by digested sludge is excluded in this study. The potential risk is generally derived from heavy metals, pathogens, hazardous organic micro-pollutants and excess nutrients. Heavy metals reside still in the stabilized sludge, whereas pathogens and micro-organic compounds can be diminished by anaerobic digestion and water contamination of excess nutrients can be also prevented by optimal land application rate [12]. Thus, only the impact of heavy metals (Table 1) and the biogenic gas of 20 g $CH_4$ and 1.1 g $N_2O$ per ton TS [26] are taken into account.

For special incineration, thickened sludge is first mechanically dewatered with the assistance of Polyacrylamide (PAM) and then thermally dried. The thermal energy is supplied by sludge organic matter and supplementary natural gas through the combustion in fluidized-bed incinerators. Semi-dry method is used to clean flue gas with the consumption of NaOH and CaO. Incineration and flue gas treatment consume electricity of 300 kWh/t TS together [12, 29]. Some pollutants are still emitted to atmosphere including dust of 15 mg/Nm$^3$, $SO_2$ of 50 mg/Nm$^3$, $NO_2$ of 125 mg/Nm$^3$, dioxins of 0.1 ng TEQ/Nm$^3$, Cd of 0.025 mg/Nm$^3$ and Hg of 0.025 mg/Nm$^3$. These are statistical data over 180 WWTPs by Ministry of Environmental Protection, China [29]. The solid residues including bottom ash and fly ash are commonly landfilled [12]. The transport distance from incineration facilities to landfill sites is set at 60 km. For well-functioning landfill sites, it is assumed that no heavy metals and other pollutants could be released from sludge ash to the environment.

For sludge co-incineration in coal-fired power plants, thermal drying is recommended as a necessary pretreatment procedure so as to maintain the steady state of boilers [29]. In this study, the pretreatment procedure of sewage sludge in coal-fired power plants is the same with that in specific sludge incineration, but the thermal energy for sludge drying is derived from the combustion of sludge organic matter and supplementary coal. Before co-incineration, dewatered sludge should be transported 60 km to power plants. Power consumption in thermal drying and co-incineration is estimated at 150 kWh/t TS referring to the operational report of the thermal power plant at Changzhou City [30, 31]. The emission from coal burning is set at half of the thresholds in the Chinese regulation GB 13223-2011 on air pollutants for thermal power plants. Similar to specific incineration, fly ash and bottom ash are also landfilled and further utilization is not included in this study in order to avoid over-expansion of the assessed system and focus on co-incineration itself.

For sludge co-incineration in cement kilns, mechanically-dewatered sludge is first dried using the waste heat in flue gas or exhausted stream from power generation units of cement kilns [32]. In cement processing, dry sludge can replace some clay (approximately 375 kg clay per ton inorganic solids in sludge) and coal (based on sludge calorific value), but increase the emission of air pollutants and the consumption of electricity (Table 2), according to the research report of Huaxin Cement plant at Yichang City [33]. The increased pollutants emission due to sludge burning and the relevant consumption of water and chemicals on flue gas treatment are referring to specific incineration, but the high temperature and the alkaline atmosphere in kilns can reduce dioxins emission significantly. The cement product from the co-incineration of sludge and other raw materials could be used in many scenarios [34], but the subsequent application and the relevant effects are not included in this assessment.

**2.3 Assessment methods**

The integrated assessment consists of three sections: environmental impact, energy efficiency and economic performance.

LCA is first carried out to assess environmental impacts. All resources and emissions that cross the system boundary are collected to compile a life cycle inventory, which is aggregated into some concerned impacts. Based on the findings, conclusions are obtained as interpretation, in order to propose an optimal choice. The CML (baseline) method is used to determine the impacts based on the world level in 2000. Seven impacts are quantified: acidification potential (AP), climate change (CC), depletion of abiotic resources (DAR), photochemical oxidation (PO), eutrophication (EU), human toxicity (HTP) and ecological toxicity (ETP). According to CML, equivalence factors are used for the characterization of each category including $SO_2$-quivalents for AP, $CO_2$ for CC, antimony and MJ for DAR (elements and fuels), ethylene for PO, $PO_4$ for EU and 1, 4-dichlorobenzene for toxicity. The normalization factors are the quantities of environmental impacts that the world contributed in 2000. The three types of ecotoxicological impacts (freshwater, marine and land) were divided by three to make the sum of them be equivalent to the other factors [12, 35]. In the same way, the two types of impacts concerning DAR (elements and fossil fuels) were divided by two. An open LCA package (OpenLCA) is used to construct a model for each approach and calculate its environmental impact.

In addition to environmental impacts, energy efficiency is important for these sludge-to-energy approaches. For each approach, the input energy includes fossil energy, electricity and the energy provided by dry sludge burning or biogas burning; the output energy is the surplus electricity in this study (in some cases no electricity can be exported). The enthalpy of input and output materials is neglected. From the view of sludge treatment, energy efficiency is defined as the ratio of sludge energy recovered in the form of biogas and heat to net energy input (the total input energy subtracting the output energy). Energy efficiency means the energy cost of recovering energy from sludge. The parameter can be schematically expressed as:

$$EE = E_{sludge} / (E_{in} - E_{out}) \quad (1)$$

Where, $EE$ is energy efficiency, $E_{sludge}$ is the energy recovered from sludge, $E_{in}$ and $E_{out}$ are the energy input into a certain system and the output from the system, respectively. When $EE$ is greater than 100%, the system could become an energy supplier.

Economic performance is also a crucial factor determining the feasibility of sludge-to-energy approaches. Net present value (NPV) method was applied to the four approaches, and a discount rate of 4.9% is used according to the current long-term loan benchmark interest rate in China. The capital expenditures are the generalized values referring to the national statistical data [29]. For unit treatment quantity (1 t TS/d), the specific capital expenditures of AD, INC, CINP and CINC are1.25, 2, 1 and 1.5 million CNY, respectively. The total operational expenditure is due to the consumption of energy and materials, the treatment of wastewater and solid residue, labor, maintenance and depreciation. The cost of energy and materials can be estimated using the data in Section 2.2 and the relevant market prices. The cost of wastewater treatment is 1.2 CNY/t referring to the relevant Charging Standard (No. [2015]119) set by China National Development and Reform Commission, and the cost of waste landfill is set at 60 CNY/t referring to the common situation [36]. The cost of labor per ton TS is estimated at 30 CNY based on the number of employees and their salaries. Maintenance cost is determined as 2% of depreciation. Depreciation is figured out using a straight-line method of 20 years with no residual value. Other financial costs are not included. The benefits are gained from saving electricity, fossil fuels and materials, while government incentives are not considered since this study focuses on the difference between these approaches. Thus, annualized net cash flows and the final NPVs can be summed using Excel software for the four approaches.

**2.4 Sensitivity and uncertainty analyses**

In the above assessments, generalized values are used to compare the four systems, but their fluctuations may possibly influence assessment results. Some methods can address this issue like one-at-a-time, method of elementary effects [37], matrix perturbation [38] and exploratory modeling [39]. In this study, four types of sludge, whose VS/TS ratios are 40%, 50%, 60% and 70%, respectively, are used as feedstock to all the systems, as mentioned in Section 2.1. Thus, the influence of sludge organic content can be discovered separately and clearly, which would be useful for specific WWTP. The other parameters were classified into several types of factors like energy consumption, chemical use and pollutant emission. Capital and operational expenditure and discount rate are also examined in economic assessment. Referring to the method of one-at-a-time and elementary effect, these factors are empirically adjusted by 30% and then the corresponding changes of assessment results are detected. Thus, the sensitive factors resulting in considerable variation of results were identified. Based on the fluctuations of these factors, the uncertainty of LCA results is further calculated using the Monte Carlo method in OpenLCA.

## 3. Results and discussion

### 3.1 Environmental impacts of sludge-to-energy approaches

Based on CML (2000), the environmental impacts are concluded in Fig. 2, and the results of sensitivity analyses are presented in Table 3. The uncertainty of the total environmental impact derived from main contributors is also exhibited as standard deviation bars in Fig. 2.

The key environmental issue of AD is ETP, which accounts for 92–97% of the total impact. The main contributors to ETP are heavy metals, including Cr (contributing 63%), As (12%) and Cu (12%). Furthermore, almost all the heavy metals released to the environment are sourced from the digested sludge spread on land. Thus, the majority of the total environmental impact is contributed by heavy metals, and this would hide the influence of variant sludge organic contents on the final result. In fact, compared with high-organic-content sludge with VS/TS 70%, low-organic-content sludge with VS/TS 40% only increase the total environmental burden by 7.1% owing to less electricity generation and more consumption of grid electricity. Thus, the uncertainty of the result is mainly derived from the variation of heavy metals content in sludge. When the contents vary from -30% to 30%, the corresponding deviation of the total environmental impact is 13.5–14.4%. Hence, it is important for AD to choose the sludge with low content of heavy metals for the final land use or treat the digested sludge in other ways so as to avoid the release of heavy metals to soil.

During INC, the total environmental impact decreases a little by 6.2% as sludge organic content decrease from 70% to 40%. CC and DAR are the major categories accounting for 52% and 30% of the sum, respectively. The main contributor to CC is biotic $CO_2$ (contributing 50–75%) from sludge combustion and abiotic $CO_2$ (50–25%) from fossil fuel combustion. The main depletion of natural resources is natural gas (more than 80% of the total) consumed on thermal sludge drying, although sludge organic matter can provide a small part of heat for water vaporization. Human toxicity is the third category contributing to the total environmental impact. The key factors relating to human toxicity are Cd (contributing 80–86%), dioxins (5–7%) and $NO_2$ (4–7%) in sequence. The sensitive factors in order are natural gas consumption, chemicals use, pollutant emission and electricity consumption (Table 3). When these factors varied in the range of -30–30%, the total environmental impacts show uncertainty degrees of 9.9–13.7%. Hence, it is important for INC to improve thermal efficiency of drying, promote energy recovery from incineration and enhance air pollution control.

Sludge can be incinerated with coal in the existing boilers of power plants. Under this situation, CC (contributing 47–50%) and AP (19–21%) become the main environmental issues. The key greenhouse gas is $CO_2$, which originates from sludge and supplementary coal for sludge drying. The AP is owing to the emission of $SO_2$ and $NO_x$. $SO_2$ is mainly produced from the consumption of grid electricity and the production of chemicals, while $NO_x$ is mainly produced from chemical production and road transportation. The third impact category is ETP (contributing 10%), which is mainly influenced by Hg emitted from coal burning. Because low-organic-content sludge needs more supplementary coal and grid electricity, the system fed with this kind of sludge would increase $CO_2$ emission and consequently increase the total environmental burden slightly by 3.1%. Main sensitive factors include electricity consumption, coal consumption, chemical use, and pollutant emission. When these factors varied in the range of -30%–30%, the uncertainty of the total impact reaches 8.7–11.1%. The supplementary coal for sludge drying is a key contributor to the total environmental impact. Compared with INC using natural gas as supplementary fuel, CINP has more environmental burden due to more emission from coal burning.

Sludge can be also disposed in cement kilns. In general, high temperature (1300–1400 °C) in kilns can reduce the formation and emission of dioxins, and the waste heat, including low-temperature flue gas and the exhausted steam after power generation from high temperature flue gas, can meet the requirement of thermal sludge drying. Under this situation, the main categories associated with the total environmental impact are AP (contributing 37–43%), toxicity (17–18%) and PO (12–13%). Acidic gases $SO_2$ and $NO_x$ are the key pollutants sourced from grid electricity generation and sludge burning. The replacement of coal and clay by dry sludge reduces the depletion of abiotic resources and fuels and also reduces the corresponding emissions. When sludge organic content decreases from 70% to 40%, the total environmental impact increases a little by 1.6%. Sensitive factors in consequence include electricity consumption, chemicals use and pollution emission. When these factors varied in the range of 30%, the uncertainty of the total impact reaches 13.9–14.5%, indicating a possible overlap of the environment impacts of CINC and INC.

The assessment results of the four approaches are very different. The main contributor to the total impact of AD is the heavy metals released to soil. For INC, CINP and CINC, the consumption of energy including grid electricity, coal and natural gas is the key factor influencing the total environmental impact. On the whole, CINC has the least environmental burden, and the order should be CINC ≤ INC < CINP <AD according to their environmental impacts. When sludge organic content decreases from 70% to 40%, the variation of the final result is limited in the range of 1.6–7.1% and it would not alter the order of the four approaches.

**3.2 Energy efficiencies of sludge-to-energy approaches**

All the four approaches aim for energy recovery from sludge, and their energy efficiencies are further calculated as shown in Fig. 3. The output energy is dependent on sludge organic content and reflected by the four types of feedstock. Thus, for each type of feed sludge, the deviation of energy efficiency originates from variant energy consumption, as shown in Fig. 3.

AD has a great advantage over the other three thermochemical pathways, mainly because it does not need energy for water evaporation. Sludge organic content has a significant impact on biogas production and energy efficiency. When sludge organic content increase from 40% to 50%, the efficiency increases sharply but the value is still lower than 100%, indicating the dependence of the system on external energy. While sludge organic content increases further to 60% and 70%, the increasing of energy efficiency slowed down, but the system can sustain itself without energy input. The surplus energy can be output in the form of electricity or heat. Hence, the energy efficiency of AD decreased by 66% when feed sludge VS/TS decreases from 70% to 40%.

For INC, CINP and CINC, the key factor relating to energy efficiency is the energy consumption on thermal sludge drying. For dewatered sludge (TS 20%), the maximum energy efficiency should be the ratio of the calorific heat of sludge solids to the heat of water vaporization in theory. According to Table 1, the maximum should be 75% to 132% corresponding to the four organic contents. However, the actual efficiencies are only 37–65%, 38–67% and 47–82%, respectively for INC, CINP and CINC, because additional energy is supplied to sludge dewatering, transportation, conversion and mechanical operation. Therefore, enhancing sludge dewatering and improving thermal drying are the two keys to improve the energy efficiency of the three approaches. For the three thermochemical systems, low-organic-content sludge (VS/TS 40%) decreases their energy efficiencies by 43%. Furthermore, CINC overwhelms CIN and CINC owing to the utilization of waste heat in flue gas or exhausted steam, which has higher thermal efficiency than the conversion from raw fossil fuels to thermal energy through combustion and heat exchange.

On the whole, AD has the highest energy efficiency, followed by CINC. CIN and CINC have similar and relatively low energy efficiencies. It should be pointed out that CINC performs as well as AD when they deal with low-organic-content sludge (VS/TS 40%). Hence, low-organic-content sludge is recommended to be treated in cement kilns since it has very limited energy potential.

### 3.3 Economic performance

Besides the environmental items mentioned above, economic performance is also an important factor determining the feasibility of a certain project and sometime it is even more important than environmental impact. Thus, a project with treatment capability of 100 t TS/d is used as a model for economic assessment. The four approaches are applied to this project, respectively. The resultant NPVs without government incentives and the operational expenditures (Oexp) are calculated as shown in Fig. 4. The main factors determining the results include capital expenditure, revenue from energy recovery, and energy cost (natural gas, coal or electricity). The latter two factors are directly related to sludge organic content, and the other expenditures have negligible influence on the final comparative results. Thus, the economic performances of the four approaches are exhibited in Fig. 4 using four types of feed sludge, as well as the uncertainty derived from variant expenditure (-30% to 30%).

The NPV results show that AD is the cheapest option on the whole, and it can even generate profit from electricity output when feeding high-organic-content sludge (VS/TS 70%). For other options, investors would not see a return within the operational life of the plant, unless they could receive government subsidies. For low-organic-content feed sludge (VS/TS 40%), CINC has similar economic performance with AD, indicating CINC is a good choice when it deals with the sludge having low potential of energy recovery. High-organic-content sludge can improve the economic performance of all the four systems to different degrees, since it can prompt biogas production and reduce energy consumption. On the whole, the NPV order is AD ≥ CINC > CINP > INC.

From the view of operational expenditure, AD is still the best but it is close to CINC when treating low-organic-content sludge. CINP and INC have no significant difference, but INC has lower NPV due to its heavy investment. The calculated full operational expenditures are consistent with the statistical data provide by Ministry of Environmental Protection, China [29], indicating the results should be effective. When sludge organic content decreases from 70% to 40%, NPVs of AD, INC, CINP and CINC decrease by 317%, 48%, 24% and 40%, respectively. The fluctuation of discount rate is also checked, but it would not alter the rank of the four approaches.

### 3.4 Comprehensive assessment

To combine the various results, the environmental, energetic and economic performances of the four approaches are ranked and scored between 1 and 4 (Table 3). The highest score means the least environmental burden, the best energy efficiency and the highest NPV. This study assesses the sustainability of these different approaches as a balance of economic and environmental impact. The results in Table 4 show CINC has advantages over AD, CINP and INC for the treatment of low-organic-content sludge, and it is also good choice for high-organic-content sludge as well as AD. For the area without suitable cement kilns, AD is the best alternative with high energy efficiency and economic superiority, but the mode of land application should be considered carefully to avoid the pollution from heavy metals. CINC is a substitute of specific incineration for many small cities in South China because it has similar environmental and energetic performance with INC but avoid big investment. However, INC is possibly necessary for some big cities because no cement kilns or coal-fired power plants are available. For the latter three approaches, decreasing the energy consumption and the cost of sludge drying is the most important to improve the integrated performance.

## 4. Conclusions

This study assesses environmental impact, energy efficiency and economic performance of four common sludge-to-energy approaches, and the effect of sludge organic content on the results is particularly paid attention to. Sludge organic content has slight influence on the total environmental impacts of the approaches, but has significant influence on their energy efficiency and economic performance. Anaerobic digestion combining land use is recommended for the treatment of high-organic-content sludge because it has the best energy efficiency and economic performance, but its environmental burden derived from heavy metals spread on land is the heaviest. Co-incineration in cement kilns is also a good alternative from a comprehensive perspective, and particularly it is the best choice for low-organic-content sludge due to less fossil energy consumption.

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## Figure captions

Fig.1 Flow charts and system boundaries of four configurations (1 anaerobic digestion; 2 Incineration; 3 Co-incineration in coal-fired power plants; 4 Co-incineration in cement kilns)

Fig.2 Life cycle impacts of four approaches using feed sludge with different organic contents (1. anaerobic digestion + land use; 2. incineration; 3.co-incineration in coal-fired power plants; 4. co-incineration in cement kilns)

Fig. 3 Energy efficiencies of four approaches treating sludge with different organic contents

Fig. 4 Net present value (NPV) and operational cost (Oexp) of four approaches treating sludge with different organic contents

Table 1 Average characteristics of the sludge used in this assessment

| Organic and nutrients | Values | Heavy metals | Values |
|---|---|---|---|
| Sludge VS/TS (%) | 40–70 | Cd (mg/kg TS) | 2.5 |
| Calorific value (kJ/kg TS) | 6800–11900 | Hg (mg/kg TS) | 2.5 |
| C (%, in VS) | 45.1 | Pb (mg/kg TS) | 150 |
| H (%, in VS) | 7.6 | Cr (mg/kg TS) | 300 |
| O (%, in VS) | 38.8 | As (mg/kg TS) | 37.5 |
| N (%, in VS) | 6.8 | B (mg/kg TS) | 50 |
| S (%, in VS) | 1.4 | Cu (mg/kg TS) | 400 |
| P (%, in TS) | 2.3 | Zn (mg/kg TS) | 1000 |
| K (%, in TS) | 0.3 | Ni (mg/kg TS) | 50 |

Table 2 Inventory of main energy and materials consumption on processes

| Processes | Unit | Value | Source |
|---|---|---|---|
| *Anaerobic digestion* | | | |
| electricity | kWh/t DS | 50 | survey |
| heat | GJ/t DS | 2.8 | survey |
| *Biogas utilization* | | | |
| electricity | kWh/t DS | 1.3–1.8 | producer |
| desulfurize | g/$Nm^3$ | 3.6 | producer |
| *High-pressure dewatering* | | | |
| electricity | kWh/t DS | 100 | [19] |
| $FeCl_3$ | kg/t DS | 30 | [19] |
| CaO | kg/t DS | 50 | [19] |
| *Dewatering* | | | |
| electricity | kWh/t DS | 50 | [17] |
| polymers | kg/t DS | 5 | [20] |
| *Thermal drying* | | | |
| electricity | kWh/t $H_2O$ | 40 | [20] |
| heat | GJ/t DS | 10.5 | [20] |
| *Incineration and flue gas treatment* | | | |
| Electricity (INC) | kWh/t DS | 300 | [20] |
| natural gas(INC) | $Nm^3$/t DS | 11 | [20] |
| Electricity (CINP) | kWh/t DS | 150 | survey |
| Electricity (CINC) | kWh/t DS | 125 | survey |
| NaOH | kg/t VS | 33.4 | [20] |
| CaO | kg/t VS | 16.7 | [20] |
| water | t/t DS | 15.6 | [20] |
| *Wastewater transport* | | | |
| electricity | kWh/t $H_2O$ | 1.05 | [13] |
| *Road transport* | | | |
| diesel | L/(t·km) | 0.02 | survey |

Table 3 Volatility of the total environmental impact corresponding to each factor's variation from -30% to 30%

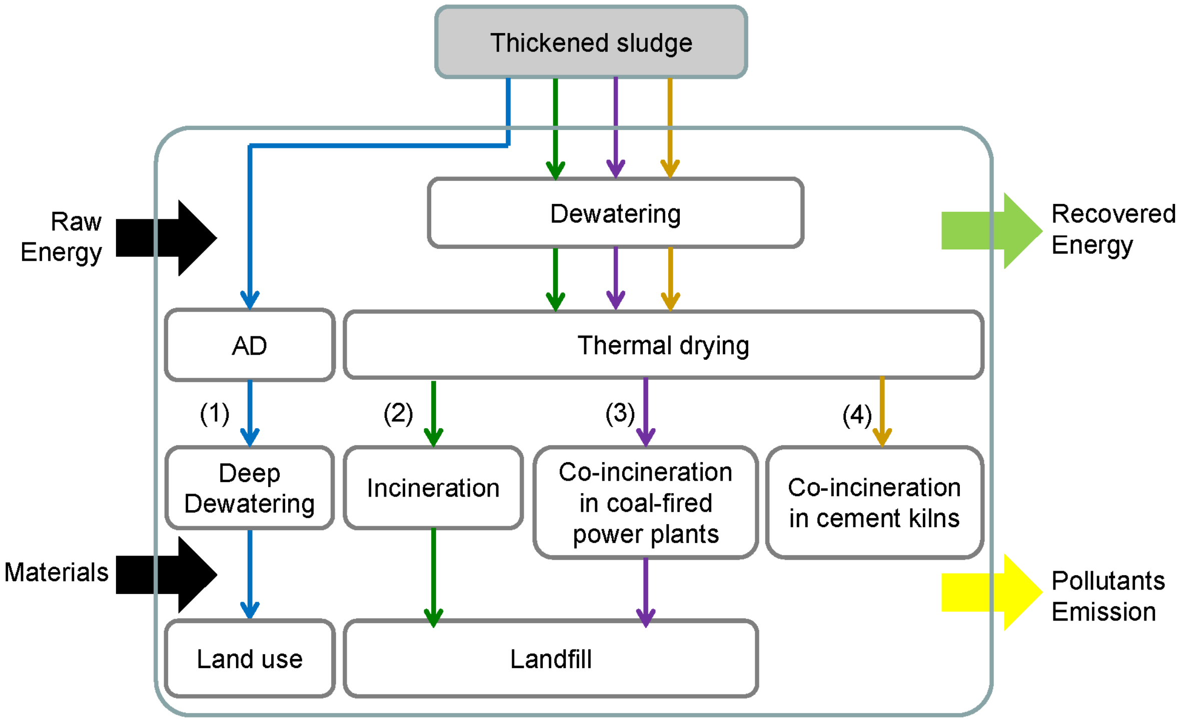
| Factors | Resultant volatility (%) | | | |
|---|---|---|---|---|
| | AD | INC | CINP | CINC |
| Electricity consumption | 0.1 | 4.5 | 10.2 | 19.9 |
| Fossil fuel consumption | 0.2 | 8.4 | 5.7 | / |
| Chemicals use | 0.2 | 7.1 | 4.6 | 8.9 |
| Pollutant emission | 29.9 | 6.4 | 4.2 | 6.8 |
| Sludge transport | 0.1 | 0.1 | 0.1 | 0.1 |

Table 4 Ranking scores of the four approaches

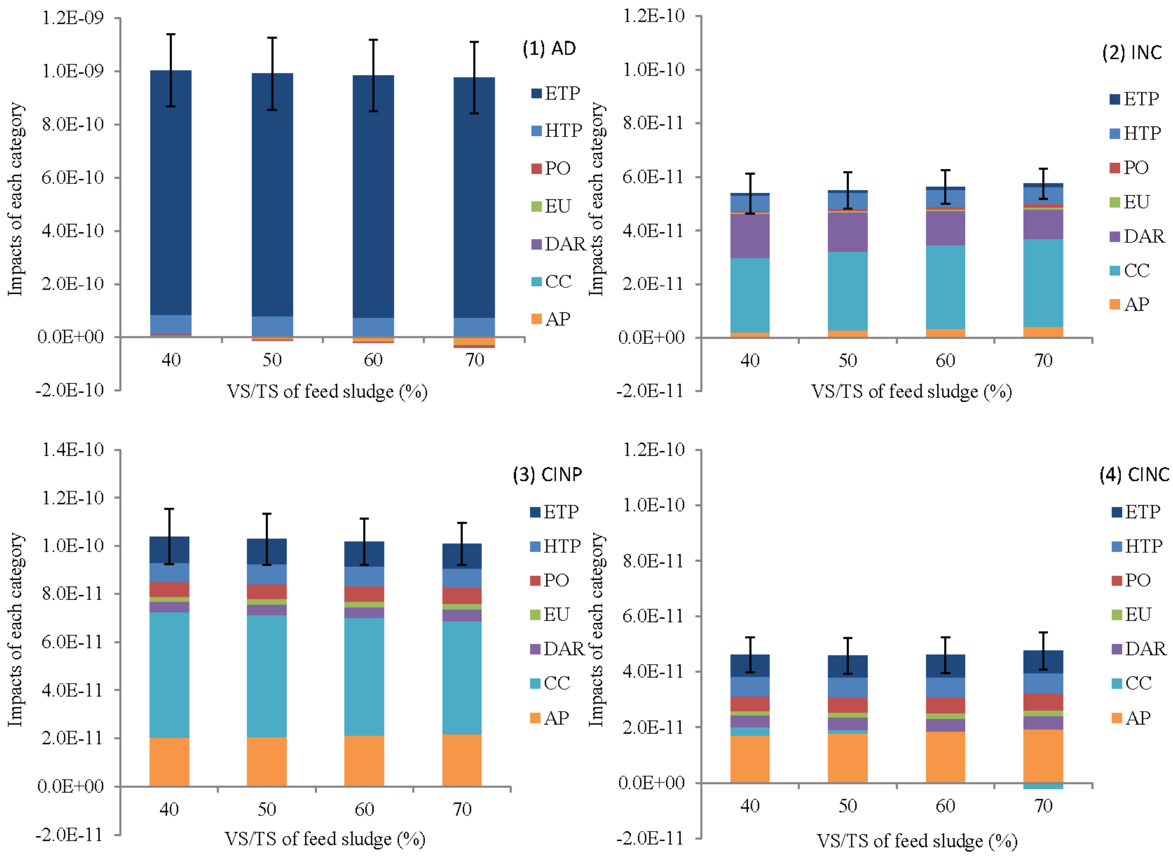
| System | Environmental impact | Energy efficiency | Economic performance | Combined total |
|---|---|---|---|---|
| AD | 1 | 4 | 4 | 9 |
| INC | 4 | 2 | 1 | 7 |
| CINP | 2 | 2 | 2 | 6 |
| CINC* | 4 | 4* or 3** | 4* or 3** | 12* or 10** |

* The score is for low-organic-content feed sludge

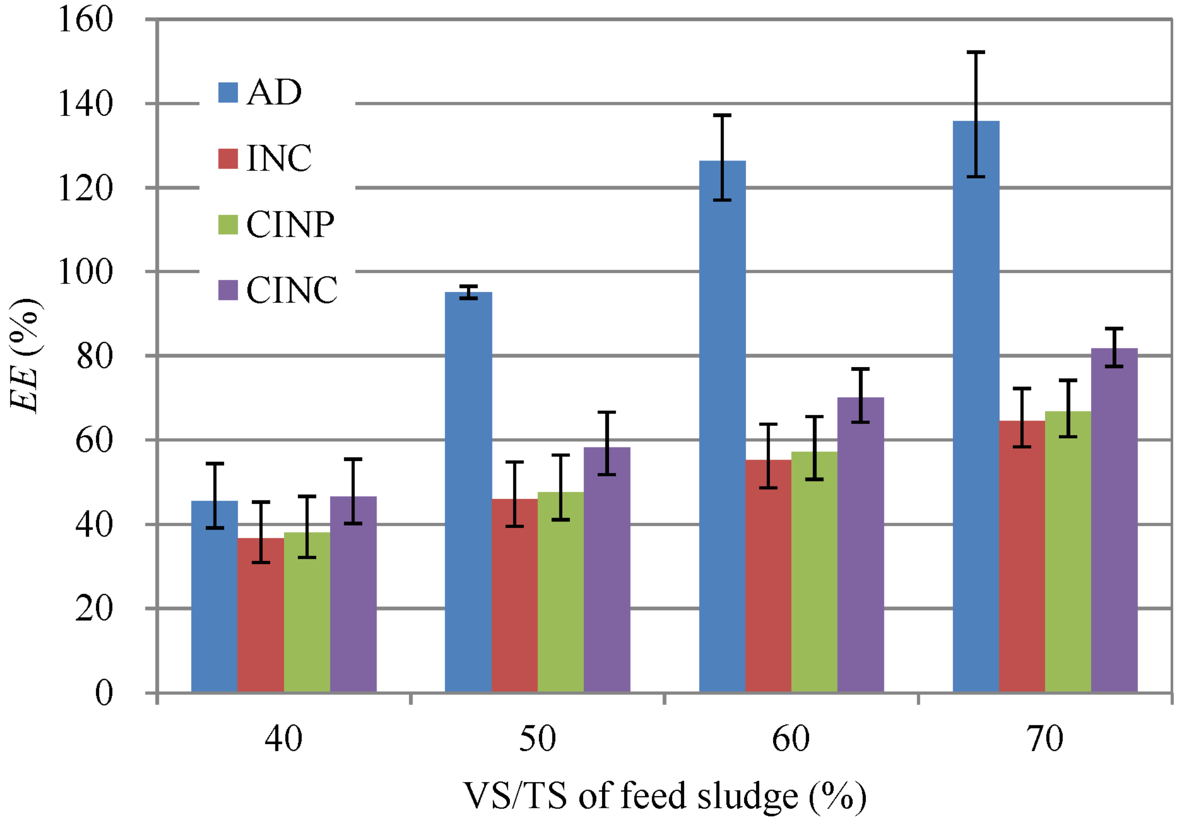
** The score is for high-organic-content feed sludge



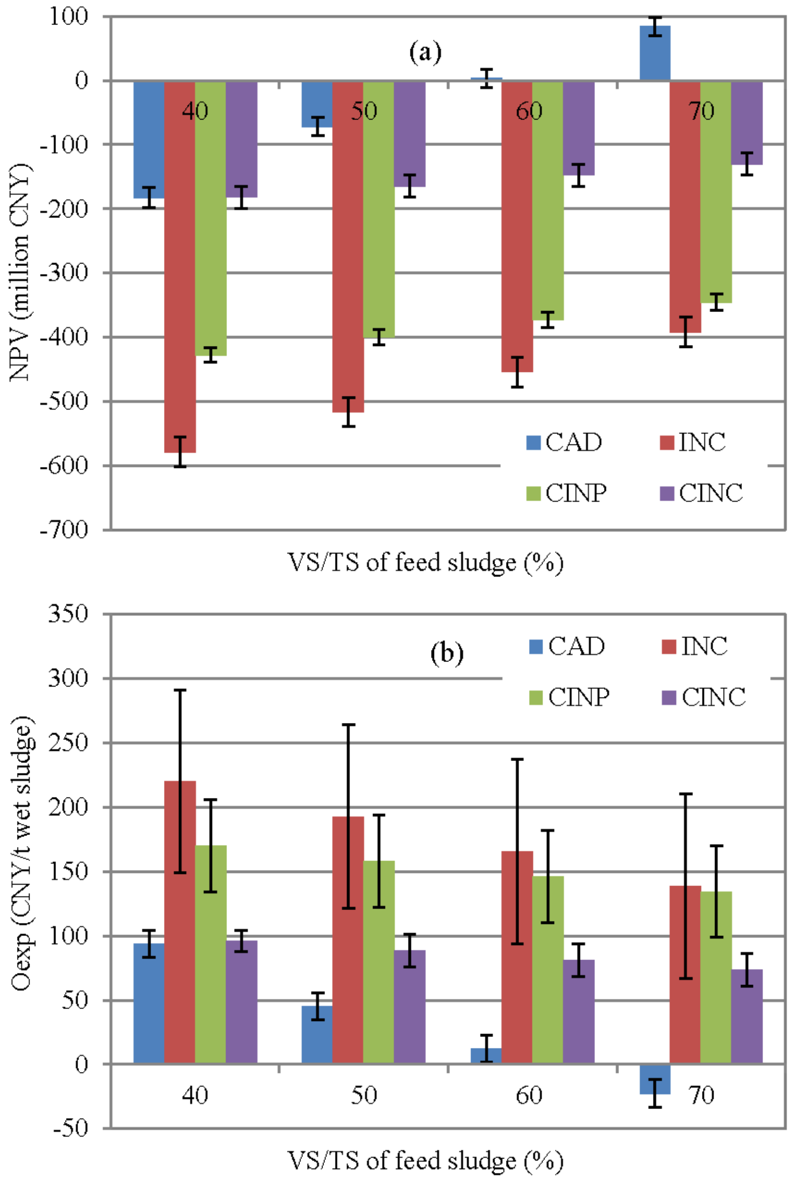
Thickened sludge
Raw Energy
Dewatering
Recovered Energy
AD
Thermal drying
(1)
(2)
(3)
(4)
Deep Dewatering
Incineration
Co-incineration in coal-fired power plants
Co-incineration in cement kilns
Materials
Pollutants Emission
Land use
Landfill



(1) AD
Impacts of each category
1.2E-09
1.0E-09
8.0E-10
6.0E-10
4.0E-10
2.0E-10
0.0E+00
-2.0E-10
40
50
60
70
VS/TS of feed sludge (%)
ETP
HTP
PO
EU
DAR
CC
AP
(2) INC
1.2E-10
1.0E-10
8.0E-11
6.0E-11
4.0E-11
2.0E-11
0.0E+00
-2.0E-11
(3) CINP
1.4E-10
1.2E-10
1.0E-10
8.0E-11
6.0E-11
4.0E-11
2.0E-11
0.0E+00
-2.0E-11
(4) CINC
1.0E-10
8.0E-11
6.0E-11
4.0E-11
2.0E-11
0.0E+00
-2.0E-11



160
140
120
100
80
60
40
20
0
EE (%)
AD
INC
CINP
CINC
40
50
60
70
VS/TS of feed sludge (%)


(a)
NPV (million CNY)
100
0
-100
-200
-300
-400
-500
-600
-700
40
50
60
70
CAD
INC
CINP
CINC
VS/TS of feed sludge (%)
(b)
Oexp (CNY/t wet sludge)
350
300
250
200
150
100
50
0
-50
40
50
60
70
CAD
INC
CINP
CINC
VS/TS of feed sludge (%)

Highlights

> Four approaches recovering energy from sewage sludge are assessed from 3E perspective

> Influence of sludge organic content on the assessment result is concluded

> Energy efficiency and economic performance decrease sharply due to low sludge VS/TS

> Co-incineration in cement kilns is the best choice for low-organic-content sludge