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Current status and trends of municipal sludge treatment and disposal in China

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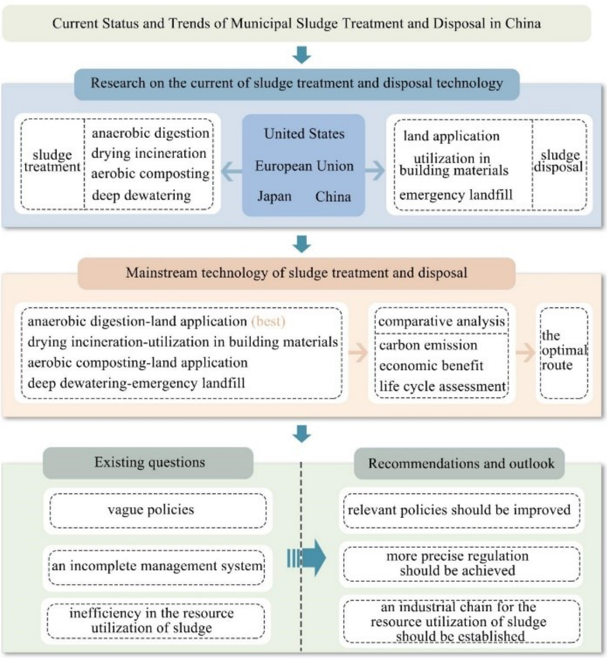
Graphical abstract



Abstract

As urbanization accelerates, an increasingly significant problem of municipal sludge treatment and disposal has emerged in China. Sludge is both a waste and a resource, therefore, its reasonable and effective treatment and disposal are crucial for protecting the environment and promoting the recycling of resources. This article reviewed the current status and technologies of sludge treatment and disposal, proposed the mainstream routes for sludge treatment and disposal in China, including anaerobic digestion-land application, drying incineration-construction material utilization, aerobic composting-land application, deep dewatering-emergency landfill. According to the comparative analysis of carbon emission, economic benefit and life cycle assessment, anaerobic digestion-land application was considered the optimal technological route. It has extremely low carbon emissions (-44.43 kg·t^{-1}) (calculated as CO_2/dry sludge), low net costs ($31.93/t) and significant environmental benefits, including SO_2 (-1.9×10^5 kg), electricity (-6.2×10^8 kWh) and fuel (-4.6×10^{7}MJ). Based on this, it highlighted the issues in sludge treatment and disposal, such as vague policies, an incomplete management system, and inefficiency in the resource utilization of sludge. In response to these issues, suggestions were made to improve relevant policies, achieve more precise regulation, and establish an industrial chain for the resource utilization of sludge.

In summary, this article offered innovative insights into the optimal technological route for sludge treatment and disposal in China, while highlighting the practical engineering significance of addressing policy, management, and resource utilization challenges. Its recommendations have the potential to drive significant improvements in sludge management practices, contributing to a cleaner, greener, and more sustainable urban environment.

Keywords: Municipal Sludge, Treatment and Disposal Technology, Carbon Emission Reduction, Economic Benefit, Life Cycle Assessment

1. Introduction

Wastewater treatment generally consists of primary, secondary, and sometimes an advanced treatment process, with different biological, physical, and chemical technologies (Batt *et al.* 2007). At present, many sewage treatment processes are used in waste water treatment plants in China, including conventional activated sludge treatment, anaerobic-anoxic-oxic, anaerobic-oxic, sequencing batch reactor, oxidation ditch, etc (Jin *et al.* 2014). During these processes, different types of sludge are produced. Primary sludge (PS) is generated by the primary settling of municipal wastewater; secondary sludge, waste activated sludge (WAS) and excess sludge are extracted from aerobic tanks or secondary settlers or return sludge lines; and mixed sludge is a combination of PS and WAS (Calabrò *et al.* 2024).

The management and treatment of these various types of sludge are crucial, with the expansion of urban areas and population growth, the production of municipal sludge in China has demonstrated an increasing trend year by year. According to statistics, China's annual sludge production reached 39.04 million tons (80% water content) in 2019 (Zhou *et al.* 2022), and this number is expected to continue growing. The growth rate of sludge production will be even more significant especially in some large cities and industrially developed regions. Municipal sludge is a major by-product of the sewage treatment process, containing a large amount of harmful substances such as organic matter, pathogens, and heavy metals, as well as carbohydrates, proteins, fats, and nutrients such as nitrogen and phosphorus (Cheng *et al.* 2022). Sludge possesses the dual characteristics of being both pollutant and resource. If not treated and disposed in a reasonable and effective manner, it will cause serious resource waste and environmental pollution, thereby endangering human health (Dai *et al.* 2022). In order to mitigate the environmental pollution caused by municipal sludge and enhance the recovery and utilization of resources within sludge, it is necessary to achieve the goals of reduction, stabilization, harmlessness, and resource utilization (Zhang *et al.* 2022).

In September 2022, the State Development and Reform Commission, the Ministry of Housing and Urban-Rural Development, and the Ministry of Ecology and Environment jointly issued the "Implementation Plan for Harmless Treatment and Resource Utilization of Sludge", providing important directives on the application of sludge treatment and disposal technologies (Xue *et al.* 2023). The Chinese environmental protection departments have explicitly stipulated that complete harmless treatment and resource utilization of sludge must be achieved by 2035 (Zhou *et al.* 2022). However, there remain a series of problems. This article summarized the current status of sludge treatment and disposal both domestically and internationally, and proposed suggestions and outlooks based on the encountered problems.

2. Current status of sludge treatment and disposal technologies

The technologies for the treatment and disposal of municipal sludge vary with different countries based on environmental policies, economic conditions, and resource feasibility.

Table 1. Sludge treatment technologies

Sludge Treatment Methods	Principle	Advantages	Disadvantages	References
Sludge Thickening Technology	The water content in the sludge is reduced by physical or chemical methods to increase the concentration of solid substances in the sludge.	A reduction in sludge volume leads to decreased transportation and processing costs.	The addition of chemical coagulant aids leads to increased treatment costs.	(Radetic 2024)
Sludge Dewatering Technology	This sludge treatment method removes water from liquid raw, thickened, or digested sludge, converting it into a semi-solid or solid clod.	Effective volume reduction, low energy consumption, minimal space requirement, and quick processing time.	The use of flocculants leads to higher treatment costs.	(Cao *et al.* 2021)
Sludge Anaerobic Digestion Technology	A biological treatment process that converts organic matter into biogas and stabilized residues through microbial metabolism under anaerobic conditions.	Odor and pathogen removal, sludge stabilization, and the production of methane as an energy source.	Inefficiency and low benefits, prolonged processing time, and demanding equipment requirements.	(Appels *et al.* 2021)
High-Temperature Aerobic Fermentation Technology	A process by which organic matter in sludge is decomposed and converted into humus-like substances through the metabolic activity of microorganisms under aerobic conditions.	Rapid processing speed, reduction in pathogens and parasites.	Increased energy consumption, and generation of odors.	(Mengqi *et al.* 2021)
Sludge Thermal Drying Technology	This technology further removes moisture from dewatered sludge to reduce its volume by transferring heat between the sludge and a thermal medium.	The volume and weight of sludge are significantly reduced, and the quality of the sludge is enhanced.	Elevated energy consumption, odor emissions, stringent equipment requirements, and increased operating costs.	(Li *et al.* 2012)

In the European Union, anaerobic digestion and aerobic fermentation are the most commonly used technologies for sludge treatment (Kelessidis and Stasinakis 2012). Regarding the final disposal of sludge, the land application of sludge is the main choice for sludge disposal in EU-15 countries, accounting for 53%. Ireland and Lithuania commonly utilize land application for sludge treatment and disposal (Hudcová *et al.* 2019), whereas Netherlands and Germany tend to prefer incineration (Kacprzak *et al.* 2017). Landfilling remains the most common method for sludge disposal in the newly joined EU countries (Kelessidis and Stasinakis 2012). In the United States, the commonly used technologies for sludge treatment are anaerobic digestion and aerobic fermentation, and the main methods of sludge disposal are land application, landfilling, and incineration (Yakamercan *et al.* 2021). According to the investigation of the U.S. Environmental Protection Agency (EPA), its sludge production in 2019 was about 4.75 million tons of dry sludge. Among them, around 2.44 million tons of dry sludge was used for land application, around 0.765 million tons of dry sludge was used for incineration, and around 1 million tons of dry sludge was landfilled and disposed of through other disposal methods (Qiu *et al.* 2023). In Japan, sludge treatment typically involves anaerobic digestion and incineration (Nakatsuka *et al.* 2020), and the main methods of sludge disposal are landfilling, and incineration (Lu *et al.* 2016).

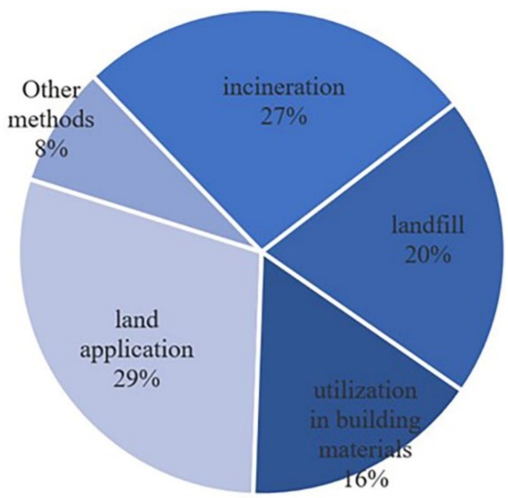


Figure 1. Proportion of Sludge Utilization and Disposal Methods in China, 2019

China's sludge treatment technologies primarily include thickening, dewatering, anaerobic digestion, high-temperature aerobic fermentation, and thermal drying (Zhen *et al.* 2017). The principles and characteristics of these technologies were detailed in Table 1. At present, incineration and anaerobic digestion occupy dominant positions (Huang *et al.* 2023). The main methods of sludge disposal include land application (Liu *et al.* 2021), incineration (Fonts *et al.* 2012), sanitary landfill (Song and Lee 2010), and utilization in building materials, as illustrated in Figure 1 (Wei *et al.* 2020). Drawing on foreign technologies, China has developed four mainstream sludge treatment and disposal technologies based on the characteristics of its sludge and regional differences, including anaerobic digestion-land application, drying incineration-utilization in building materials, aerobic composting-land application, and deep dewatering-emergency landfill, as shown in Figure 2.

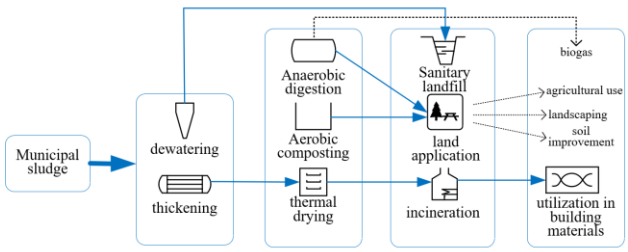


Figure 2. Mainstream Routes for Sludge Treatment and Disposal

2.1. Anaerobic digestion-land application

Anaerobic digestion-land application refers to the application of stabilized sludge from anaerobic digestion to agricultural fields, gardens, green belts, and other lands, acting as a soil conditioner or fertilizer. It is an effective method of sludge treatment and disposal (Yakamercan *et al.* 2021). This process not only stabilizes the biodegradable organic matter in the sludge, reducing the number of pathogens and the volume of sludge (Dai *et al.* 2021), but also recovers organic matter and nutrients from the sludge, aiding in soil structure improvement and plant growth promotion (Elmi and AlOlayan 2020). Simultaneously, it features low energy consumption and negative carbon emissions (Zhao *et al.* 2024), playing a crucial role in achieving environmental sustainability (Xu *et al.* 2021).

In China, combining anaerobic digestion with land application has become the preferred technological route for the treatment and disposal of sludge (Feng *et al.* 2015). According to Calabro's *et al.* (2024) statistical analysis, during anaerobic digestion, Eastern Asia, where the data were concentrated in China, Japan and South Korea, has the lowest mean bio-methane yield, with only 0.148 Nm^3 kg_{VS}^{-1}. Only the geographical area, the experiment date and the digested sludge type significantly influenced the bio-methane yield. It may be that the relatively low biodegradability of organic matter in municipal sludge in China leads to the lower efficiency of anaerobic digestion process and the reduction of methane production. Optimizing anaerobic digestion technology can effectively degrade organic matter and increase gas production. For example, research has demonstrated that the use of interspecies hydrogen transfer, hydrogen partial pressure, and microbial electrochemical systems can improve the overall efficiency of the anaerobic digestion process by enhancing the synthetic interactions among different microorganisms (Anukam *et al.* 2019). In addition, anaerobic digestion treatment can co-digest municipal sludge, food waste, and livestock and poultry manure, as well as other organic wastes, improving sludge treatment efficiency while increasing the production of biogas. Lan Mu *et al.* (2020) conducted a series of co-digestion anaerobic digestion experiments in a semi-continuous mode with different types of municipal sewage sludge, kitchen waste, and yard waste from different cities. As for co-anaerobic digestion of three feedstocks, high methane yields of 314.9 ± 17.1 mL/g VS were achieved with a reliable stability. The results indicated that co-digestion anaerobic digestion not only improved methane yield, content, and production, but also promoted the sustainability of waste management and energy utilization.

After anaerobic digestion, the impact on methanogenic bacteria can significant, potentially lead to severe acidification of the system (Zeng *et al.* 2020). Although the organic content of the sludge decreases, this does not diminish its value for land application (Feng *et al.* 2015). However, the potential environmental risks must be considered when using sludge for land application. Sludge contains harmful substances such as heavy metals and pathogens, which may pollute the soil and groundwater if not properly treated or used excessively. Therefore, a comprehensive assessment of the toxic and carcinogenic chemicals contained in sludge must be conducted before its land application (Yakamercan *et al.* 2021). During land application, it is necessary to strictly control the amount and frequency of sludge application, continuously monitor its impact on the concentration of heavy metals in crops, and ensure its environmental and agricultural safety (Cocârță *et al.* 2019).

2.2. Drying incineration-utilization in building materials

Sludge drying and incineration technology involves two steps: drying and incineration. Firstly, the moisture in the sludge is evaporated through thermal drying, transforming wet sludge into dried sludge (Gao *et al.* 2023). This not only reduces the volume of the sludge but also prepares the dry material for the subsequent incineration process, thereby improving the efficiency of incineration (Xue *et al.* 2023). Then, the dried sludge undergoes high-temperature aerobic combustion (Dai 2020), which can completely decompose the organic matter in the sludge, eliminate pathogens and microbes, and stabilize heavy metals. Drying and incineration can reduce the volume of sludge by more than 90% (Dai *et al.* 2021). The ash produced after sludge incineration can serve as raw materials or additives for construction materials (Ni *et al.* 2022), utilized in the production of lightweight aggregates, biochemical fiberboards, vitrified aggregates, sludge bricks, pipeline bedding materials, roadbed aggregates, etc (Zeng *et al.* 2020). This not only achieves resource utilization of sludge, but also reduces the dependence on natural resources, which has environmental and economic value (Ducoli *et al.* 2021).

In densely populated, economically developed cities with concentrated sludge production and scarce land resources, the drying and incineration technology route is often preferred (Duan *et al.* 2023). Nena Duan *et al.* (2023) utilized Aspen Plus software to construct a process model of sludge drying and incineration and conducted an energy optimization configuration of thermal engineering design through multi-factor correlation analysis. This established a steady-state operation model of China's typical sludge drying and incineration process “conductive thermal drying-fluidized bed incineration-flue gas residual heat preheats air and supplements drying thermal energy” (Yang *et al.* 2021).

Although the drying incineration-building material utilization route has demonstrated good environmental protection and resource utilization effects in sludge treatment and disposal, the drying and incineration processes may produce harmful substances, such as dioxins, posing threats to the environment and human health. Additionally, the incineration process is characterized by high energy consumption and requires significant energy input. Currently, sludge drying and incineration technology have been optimized and improved through deep integration across multiple fields. For example, Franco Falconi *et al.* (2020) utilized Linear Quadratic Regulator optimized waste-to-energy incineration technology, which addressed the shortcomings of traditional Single Input Single Output strategies. This approach reduced the emission of pollutants by controlling steam flow to manage energy production and ensuring complete combustion (Falconi *et al.* 2020). Simultaneously, a perfected intelligent sensing system has been implemented in current sludge drying and incineration projects, achieving automation and intelligence (Zhang 2023).

2.3. Aerobic composting-land application

Aerobic composting can be applied to various organic wastes, including sludge from sewage treatment plants and agricultural waste. In this process, sludge and organic matter are thoroughly mixed and composted under moist, ventilated, and high-temperature conditions, achieving harmless treatment and resource utilization of sludge (Nowak 2006). The construction and maintenance costs of the aerobic composting treatment and disposal process are relatively low. Additionally, the simple process of operation and management and the high stability makes it suitable for land application (Dai 2020). However, this technological process has some disadvantages, such as slow process, occupying a large area, and having a threaten to the environment and human health. Therefore, Cheng Qingli *et al.* (2021) utilized enzymatic pretreatment combined with biological fortification to optimize the urban sludge aerobic composting technology. The mass fractions of soluble chemical oxygen demand, soluble protein, and polysaccharides in the sludge increased by 485.22%, 149.15% and 108.76%, thereby improving the efficiency of sludge aerobic composting, reducing the start-up time of compost fermentation. Moreover, the addition of fortified microbial agents showed significant nitrogen preservation effects and reduced odor release, achieving rapid and efficient resource utilization of urban sludge.

Currently, the ecological risks associated with the land application of aerobic composting products of sludge are receiving increasing attention (Chang *et al.* 2019). Zheng *et al.* (2021) composted sludge contaminated with triclocarban (TCC) using wood chips and straw, respectively. The biodegradation of TCC is influenced by factors such as the type of bulking agents and the duration of composting. After land application, the soil concentrations of TCC were 2.30 ng g^{-1} and 4.45 ng g^{-1}, respectively. Following a risk assessment, the recommended the maximum application amounts for these two types of compost products are 35.0 t hm^{-1} (for wood chip compost) and 18.0 t hm^{-1} (for straw compost).

2.4. Deep dewatering-emergency landfill

Through deep dewatering, the water content of sludge can be reduced to a considerably low level, thus reducing the space and cost for subsequent treatment and disposal (Cao *et al.* 2021). However, leachate is generated in the process, which may contain a large number of organic matter, heavy metals, nutrient salts and other pollutants. If not properly treated, the leachate will pollute the surrounding surface water and groundwater, causing serious damage to the ecological environment. Emergency landfill refers to the temporary or long-term underground storage of treated sludge in specific landfill sites. In this process, a large number of greenhouse gases such as CH_4 and N_2O are released in a disorderly manner, thus increasing carbon emissions. Deep dewatering-emergency landfill is a widely adopted sludge treatment and disposal technology in China. It is a low-cost method, but this technology causes serious secondary pollution, occupies land, wastes resources, and high carbon emissions. It is considered only as an emergency treatment method (Xu *et al.* 2021), serving as a transitional treatment and disposal approach (Dai *et al.* 2021).

Currently, more mature technologies for advanced sludge dewatering include physicochemical methods such as acid treatment, advanced oxidation technologies, and thermal treatment, as well as biodegradation methods, aimed at optimizing the dewatering performance and economic aspects of sludge (Dai 2020). For example, Xie *et al.* (2022) synthesized poly dimethyl diallyl ammonium chloride through radiation synthesis and combined it with polyaluminum chloride and calcium oxide as conditioning agents for advanced sludge dewatering, thereby optimizing the dewatering effect.

In practice, both the background and actual concentrations of toxic metals in the soil should be taken into consideration, when soils for the disposal of sewage sludge are selected.

2.5. Comparative analysis of four mainstream technologies for sludge treatment and disposal

With the deep implementation of the dual carbon policy, carbon emissions have become an important indicator for selecting sludge treatment and disposal technologies. Research by Dai *et al.* (2021) had shown that the method with the highest carbon emissions is landfilling after deep dewatering, followed by sludge drying and incineration. Aerobic fermentation followed by land application has lower emissions, with the lowest carbon emissions being from land application after anaerobic digestion. On the other hand, Li *et al.* (2023) calculated the carbon emissions of each unit of sludge treatment and disposal, such as thermal drying (1049.24 $kg{\cdot}t^{-1}$), deep dewatering (960.99 $kg{\cdot}t^{-1}$), sanitary landfill (786.24 $kg{\cdot}t^{-1}$), incineration (635.52 $kg{\cdot}t^{-1}$), anaerobic digestion (371.4 $kg{\cdot}t^{-1}$) and aerobic composting (614.17 $kg{\cdot}t^{-1}$). The main carbon compensation methods include land application (-415.83 $kg{\cdot}t^{-1}$) and building material utilization (-169.75 $kg{\cdot}t^{-1}$). Taking a comprehensive view, the carbon emission of anaerobic digestion-land application is -44.43 $kg{\cdot}t^{-1}$. Therefore, this technological route has greater carbon offset potential and better environmental friendliness (Figure 3).

From an economic perspective, the land application route is cost-effective and offers high benefits, as illustrated in Figure 4. Additionally, it features higher tolerance for errors, energy recovery functions, and is environmentally friendly. In contrast, the use of building materials yields lower benefits (Wang *et al.* 2023). Consideration cost, economic benefits, and the principles of green and low carbon, for municipal sludge treatment and disposal, it is recommended to prioritize land use, with the use in building materials as a secondary option. From the net costs perspective, aerobic composting-land application ($29.58/t) is the most economical waste treatment route, followed by anaerobic digestion-land application ($31.93/t). The cost difference between the two routes is $2.35 per ton of sludge treated, which is relatively small.

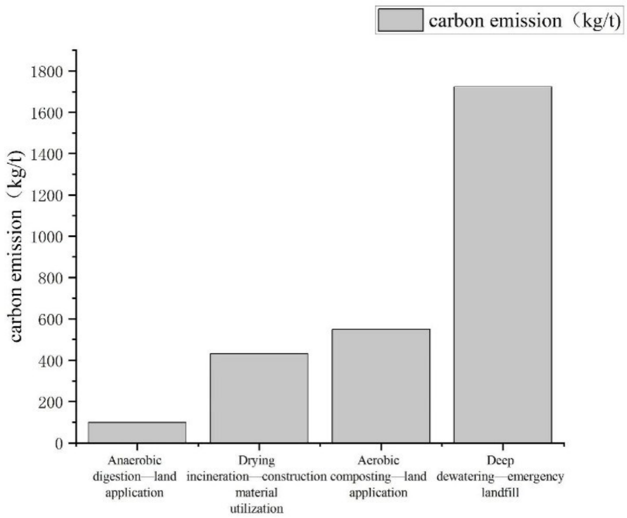


Figure 3. Carbon Emission Diagram of Mainstream Technologies for Sludge Treatment and Disposal

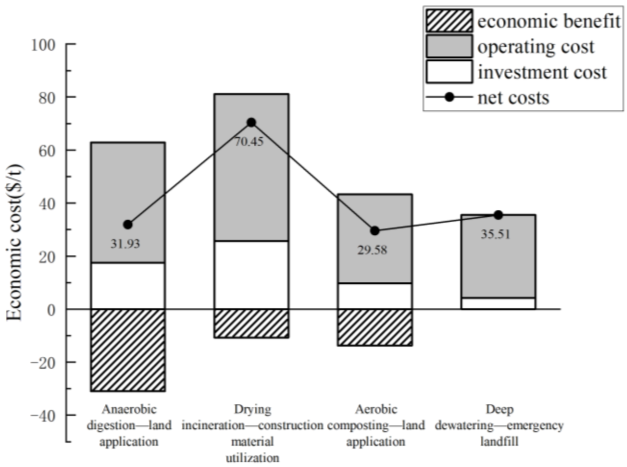


Figure 4. Economic Cost Diagram of Sludge Treatment and Disposal Routes

A comprehensive life cycle assessment identifies anaerobic digestion as the best sludge treatment technology (Xu *et al.* 2014). Regarding sludge disposal methods, using sludge as fertilizer for land application shows the best results. As indicated in Table 2, anaerobic digestion-land applications can reduce SO_2 emissions by about $1.9{\times}10^5$ kg, save about $6.2{\times}10^8$ kWh of electricity consumption and about $4.6{\times}10^7$ MJ of fuel consumption. This technical route provides the largest electricity offsets and the lowest fuel consumption (Murray *et al.* 2008). Considering carbon emissions, economic benefits and life cycle assessment, anaerobic digestion-land application becomes the preferred technology for sludge treatment and disposal due to its low carbon emissions, high economic benefits and significant environmental advantages.

3. Problems faced by sludge treatment and disposal

3.1. Policy provisions are not yet clear

Currently, Chinese government departments are increasingly focusing on sludge treatment and disposal, continuously clarifying the development direction of sludge treatment and disposal technologies from the "13th Five-Year Plan" to the "Water Ten Articles" and then to the "14th Five-Year Plan". However, specific policies related to sludge treatment and disposal are scarce (Lu *et al.* 2024), with a lack of mandatory provisions, standards, and engineering application technical guidelines (Xue *et al.* 2023). For instance, the "Implementation Plan for Harmless Treatment and Resource Utilization of Sludge" explicitly highlights the necessity of selecting reasonable and diversified technology combinations based on local conditions but fails to provide specific application methods (such as methods, seasons, frequency) for sludge treatment and disposal. Moreover, national policies concentrate on controlling pollutant indicators before sludge treatment and disposal, but fail to establish an environmental and ecological risk assessment system for the sludge treatment and disposal process (Cheng *et al.* 2019).

Economically, China's annual investment in sludge treatment and disposal amounts to approximately 5.53 billion US dollars, in contrast to about 68.11 billion US dollars annually for wastewater treatment. However, in developed countries, the investment ratio between sludge treatment and wastewater treatment is approximately equal (Cocârță *et al.* 2019). This indicates insufficient investment in sludge treatment and disposal in China, resulting in the current situation where it remains at the harmless treatment stage, whereas developed countries have largely achieved the recycling and utilization of resources (Dai *et al.* 2022). Simultaneously, policies regarding economic incentives such as charges, taxes, and subsidies are not sufficiently specific and clear, and the costs of sludge treatment and disposal have not been effectively integrated into the standards, resulting in a lack of economic policies to foster industry development.

3.2. Management standard system is incomplete

China's sewage plants, being of a large scale, produce concentrated amounts of sludge. However, due to an incomplete regulatory framework, there are gaps in supervision and instances of inadequate oversight. To reduce costs, some sewage treatment plants resort to unorganized emissions, private landfilling, or direct incineration for disposing of large quantities of sludge. These methods not only damage the soil and groundwater but also squander the potential for resource utilization of organic matter in the sludge (Dai *et al.* 2022).

Regarding top-level design, China lacks both a comprehensive management standard system and a multi-party coordinated management mechanism (Yang *et al.* 2015). During the management process of sludge treatment and disposal, sludge management institutions exhibit inconsistent standards (Lv *et al.* 2012), involving multiple departments and units, including environmental protection departments, municipal departments, and sewage treatment enterprises. However, the responsibilities and authorities of various management entities have not been clearly defined, potentially leading to management confusion and buck-passing.

Table 2. Environmental Assessment of Mainstream Technologies for Sludge Treatment and Disposal

Mainstream Technologies of Sludge Treatment and Disposal	SO_2(kg)	Electricity(kWh)	Fuel(MJ)
Anaerobic digestion-land application	-1.9×10^5	-6.2×10^8	-4.6×10^7
Drying incineration-construction material utilization	1.4×10^6	-3.2×10^7	7.1×10^8
Composting-land application	1.2×10^4	-5.9×10^8	8.3×10^7
Deep dewatering-emergency landfill	4.0×10^3	5.7×10^5	2.8×10^6

Note: positive values represent the emissions or consumption of the indicator, while negative values represent the net savings or recovery of the indicator.

3.3. Sludge resource utilization is not smooth

China's municipal sludge is characterized by its large volume, high moisture content, and high organic content, distinguishing it from sludge in other countries. This difference results in bottlenecks in adopting foreign technologies and equipment, as well as in implementing mature technology routes (Zhang *et al.* 2022). Additionally, each method has its downsides, which makes the choice of technology route unclear. Meanwhile, the underdevelopment of sewage treatment systems and sludge treatment facilities hampers sludge resource utilization (Qu *et al.* 2019).

The current standards for sludge treatment and disposal are fragmented and disjointed. And these standards mandate that sewage treatment plants adopt a "one-size-fits-all" approach without considering the entire process of sludge treatment, transportation, and disposal. Moreover, there is an absence of the mindset that sludge disposal decisions should guide sludge treatment processes (Hu 2019).

4. Recommendations and outlook for sludge treatment and disposal

4.1. Policies related to sludge treatment and disposal technologies should be improved

Technical guides and specialized technical specifications for urban sludge resource utilization should be developed in detail. First, these documents should elaborate on the main technological routes and methods currently employed for sludge resource utilization, as well as the corresponding directions for product development. Second, technical guides should provide comprehensive technical parameters, operating procedures, and safety guidelines for various technical paths. Finally, these policies should clarify the quality standards and environmental protection requirements of sludge treatment and disposal for resource utilization. This will provide clear operational guidance and an evaluation basis for sludge harmless treatment and resource utilization.

In financial terms, the government should encourage enterprises and research institutions to engage in technological innovation and product development by providing incentives such as financial subsidies, tax reductions, and green finance. Besides, a special fund should be established to specifically support scientific research, development, and demonstration projects for the resource utilization of sewage sludge, which will provide solid financial support for the harmless treatment and resource utilization of sludge.

4.2. Sludge treatment and disposal process to achieve refined regulation

In the process of sludge treatment and disposal, it is necessary to establish a comprehensive regulatory and tracking system. In detail, this system should encompass every stage, from generation, collection, transportation, and processing, to the final utilization. This system ensures the transparency and traceability of information to facilitate the timely discovery and resolution of problems. Simultaneously, the key parameters of sludge treatment should be monitored in real time, such as temperature, pH value, and the content of harmful substances. This is crucial for maintaining the stability of the treatment process and ensuring the safety of the final product.

Moreover, departments should enhance coordination and cooperation by establishing a cross-departmental coordination mechanism composed of environmental protection, urban construction, agriculture, water affairs, and other departments. This mechanism should foster a synergistic development pattern for sludge treatment, disposal, and resource utilization. In addition, wastewater treatment plants must strictly uphold the direct responsibilities of their governing departments and improve the management of the sludge treatment and disposal process. Furthermore, they should tighten the regulation of pollutant emissions in industrial processes and clearly delineate the pathways for harmless treatment. These pollutants from the sludge treatment process are ensured to be harmless before being discharged into the system.

4.3. Each link interlocks to create an industrial development chain for the resource utilization of sludge

Research institutions should conduct in-depth market demand analysis for products derived from sludge transformation to guide product development and marketing strategies. Then this will encourage more enterprises to adopt a product-oriented approach to sludge treatment and disposal, and to explore the potential to convert sludge into a variety of products, including bio-fertilizers, soil conditioners, building materials, and bioenergy. Thereby these research applications increasing the utilization pathways and enhancing the market value of sludge. Moreover, the state must establish a rigorous quality control system and participate in or promote the development of relevant product standards, to ensure the quality and safety of products transformed from sludge. In addition, the productization of sludge after treatment and disposal effectively introduces market capital and reduces the excessive reliance on government subsidies for sludge treatment and disposal. And then, the potential of sludge treatment and disposal has been activated to achieve sustainable development of sludge treatment and disposal in China.

Acknowledgments

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References

Anukam A., Mohammadi A. and Naqvi M. *et al.* (2019). A review of the chemistry of anaerobic digestion: Methods of accelerating and optimizing process efficiency, *Processes*, **7**, 504.

Appels L., Baeyens J., Degrève J. *et al.* (2021). Principles and potential of the anaerobic digestion of waste-activated sludge, *Progress in Energy and Combustion Science*, **34**, 755–81.

Batt A. L., Kim S. and Aga D. S. (2007). Comparison of the occurrence of antibiotics in four full-scale wastewater treatment plants with varying designs and operations, *Chemosphere*, **68**, 428-435.

Calabrò P. S., Elbeshbishy E., Laqa Kakar F. *et al.* (2024). A short bibliographic review concerning biomethane production from wastewater sludge, *Waste Management & Research*.

Cao B., Zhang T., Zhang W. *et al.* (2021). Enhanced technology based for sewage sludge deep dewatering: A critical review, *Water research*, **189**, 116650.

Chang R., Yao Y., Cao W. *et al.* (2019). Effects of composting and carbon based materials on carbon and nitrogen loss in the arable land utilization of cow manure and corn stalks, *Journal of environmental management*, **233**, 283-290.

Cheng X., Wei C., Ke X. *et al.* (2022). Nationwide review of heavy metals in municipal sludge wastewater treatment plants in China: Sources, composition, accumulation and risk assessment, *Journal of Hazardous Materials*, **437**, 129267.

Cheng L., Wang L., Geng Y. *et al.* (2019). Occurrence, speciation and fate of mercury in the sewage sludge of China, *Ecotoxicology and Environmental Safety*, **186**, 109787.

Cheng Q. L., Wang D. W., Niu B. C. *et al.* (2021). Enzymatic hydrolysis pretreatment combined with bioaugmentation optimization for urban sludge aerobic composting, *Ecology and Environmental Sciences*, **30**, 2395-2401.

Cocârță D. M., Velcea A. M. N., Harber C. *et al.* (2019). Benefits and potential risks to humans from agricultural use of sewage sludge, *Proceedings of the 19th International Multidisciplinary Scientific GeoConference SGEM, Bulgaria*, **19**, 177-184.

Dai X., Li H., Zhang L. *et al.* (2022). Safe disposal and resource recovery of urban sewage sludge in China, *Strategic Study of Chinese Academy of Engineering*, **24**, 145-153.

Dai X. H. (2020). Current status and development trends of sludge treatment and disposal in China, *Science*, **72**, 30-34+4.

Dai X. H., Zhang C., Zhang L. W. *et al.* (2021). Reflections on the development direction of sludge treatment, disposal, and resource utilization under the context of carbon neutrality, *Water Supply and Drainage*, **57**, 1-5.

Duan N. N., Tan X. J. and Zhang C. (2023). Thermodynamic simulation and optimization of sludge drying and incineration in wastewater treatment plants based on Aspen Plus, *Water Supply and Drainage*, **59**, 22-28.

Ducoli S., Zacco A. and Bontempi E. (2021). Incineration of sewage sludge and recovery of residue ash as building material: A valuable option as a consequence of the COVID-19 pandemic, *Journal of Environmental Management*, **282**, 111966.

Elmi A. and AlOlayan M. (2020). Sewage sludge land application: Balancing act between agronomic benefits and environmental concerns, *Journal of Cleaner Production*, **250**, 119512.

Falconi F., Guillard H., Capitaneanu S. *et al.* (2020). Control strategy for the combustion optimization for waste-to-energy incineration plant, *IFAC-PapersOnLine*, **53**, 13167-13172.

Feng L., Luo J. and Chen Y. (2015). Dilemma of sewage sludge treatment and disposal in China, *Environmental Science & Technology*, **49**, 4781-4782.

Fonts I., Gea G., Azuara M. *et al.* (2012). Sewage sludge pyrolysis for liquid production: a review, *Renewable and Sustainable Energy Reviews*, **16**, 2781-2805.

Gao W. M. and Cheng H. F. (2023). Research progress on sludge treatment and disposal technology in China, *Chemical Industry and Engineering Progress*, **52**, 71-79.

Hu W. J. (2019). Several aspects that need to be considered in the treatment and disposal of sludge in China's wastewater treatment plants, *Water Supply and Drainage*, **55**, 35-41.

Huang Y., Zhen Y., Liu L. *et al.* (2023). Comprehensive competitiveness assessment of four typical municipal sludge treatment routes in China based on environmental and techno-economic analysis, *Science of The Total Environment*, **895**, 165123.

Hudcová H., Vymazal J. and Rozkošný M. (2019). Present restrictions of sewage sludge application in agriculture within the European Union, *Soil & Water Research*, **14**, 104-120.

Jin L., Zhang G. and Tian H. (2014). Current state of sewage treatment in China, *Water research*, **66**, 85-98.

Kacprzak M., Neczaj E., Fijałkowski K. *et al.* (2017). Sewage sludge disposal strategies for sustainable development, *Environmental research*, **156**, 39-46.

Kelessidis A. and Stasinakis A. S. (2012). Comparative study of the methods used for treatment and final disposal of sewage sludge in European countries, *Waste management*, **32**, 1186-1195.

Li R. D., Zhang W. L., Sun Y. *et al.* (2012). Adaptability analysis of sludge thermal drying technology and future development trends, *Renewable Energy*, **30**, 95-99.

Li Z. K., Zhang L. Q., Du Z. W. *et al.* (2023). Comparison of carbon emissions from different treatment and disposal processes for urban sludge, *Environmental Science*, **44**, 1181-1190.

Liu L., Ye Q., Wu Q. *et al.* (2021). Effect of biochar addition on sludge aerobic composting and greenbelt utilization, *Environmental Technology & Innovation*, **21**, 101279.

Lu H., Wang C., Zhang B. *et al.* (2024). Discussion on the current situation and problems of industry policies for municipal sludge treatment and disposal in China, *Construction Science and Technology*, 78-80.

Lu W. S., Li J. S. and Jiang B. J. (2016). Sewage sludge treatment and disposal methods in developed countries, *China Resources Comprehensive Utilization*, **34**, 27-29.

Lv J., Bu X. M., Li J. Y. *et al.* (2012). Study on Optimizing the Managerial Strategies of Municipal Sludge Treatment and Disposal in a City of Northern China, *Applied Mechanics and Materials*, **178**, 950-953.

Mengqi Z., Shi A., Ajmal M. *et al.* (2021). Comprehensive review on agricultural waste utilization and high-temperature fermentation and composting, *Biomass Conversion and Biorefinery*, **13**, 1-24.

Mu L., Zhang L., Zhu K. *et al.* (2020). Anaerobic co-digestion of sewage sludge, food waste and yard waste: Synergistic enhancement on process stability and biogas production, *Science of the total environment*, **704**, 135429.

Murray A., Horvath A. and Nelson K. L. (2008). Hybrid life-cycle environmental and cost inventory of sewage sludge treatment and end-use scenarios: a case study from China, *Environmental science & technology*, **42**, 3163-9.

Nakatsuka N., Kishita Y., Kurafuchi T. *et al.* (2020). Integrating wastewater treatment and incineration plants for energy-efficient urban biomass utilization: A life cycle analysis, *Journal of cleaner production*, **243**, 118448.

Ni T., Xu F., Gao C. *et al.* (2022). Chemical activation of pozzolanic activity of sludge incineration ash and application as row bonding materials for pervious ecological brick, *Construction and Building Materials*, **329**, 127199.

Nowak O. (2006). Optimizing the use of sludge treatment facilities at municipal WWTPs, *Journal of Environmental Science and Health Part A*, **41**, 1807-1817.

Qiu F. X., Hu W. J., Lu J. Y. *et al.* (2023). Analysis and revelation of flue gas emission standard of sewage sludge incineration in USA, *Water & Wastewater Engineering*, **59**, 158-164.

Qu J., Wang H., Wang K. *et al.* (2019). Municipal wastewater treatment in China: Development history and future perspectives, *Frontiers of Environmental Science & Engineering*, **13**, 1-7.

Radetic B. (2024). Municipal Sludge Thickening Technologies, Handbook of Water and Used Water Purification, Cham: Springer International Publishing.

Song U. and Lee E. J, (2010). Environmental and economical assessment of sewage sludge compost application on soil and plants in a landfill, *Resources, conservation and recycling*, **54**, 1109-1116.

Wang J. Y., Chen W., Wu Y. Z. *et al.* (2023). Economic analysis and evaluation of municipal sludge treatment and disposal technology, *Journal of Environmental Engineering*, **17**, 2695-2704.

Wei L., Zhu F., Li Q. *et al.* (2020). Development, current state and future trends of sludge management in China: Based on exploratory data and CO2-equivaient emissions analysis, *Environment International*, **144**, 106093.

Xie H. K., Zhao C. F., Yu W. D. *et al.* (2022). Radiation synthesis of PDMDAAC and its application in deep dewatering of sludge, *Chemical Research and Application*, **34**, 904-908.

Xu C., Chen W. and Hong J. (2014). Life-cycle environmental and economic assessment of sewage sludge treatment in China, *Journal of Cleaner Production*, **67**, 79-87.

Xu Y., Liu R., Yang D. *et al.* (2021). Sludge treatment and resource recovery towards carbon neutrality in China: current status and future perspective, *Blue-Green Systems*, **3**, 119-127.

Xue Z. Y., Meng Q. Y., Yang L. Q. *et al.* (2023). Current status and prospects of urban sewage sludge treatment and disposal. *Beijing Water Affairs*, 39-43+61.

Yakamercan E., Ari A. and Aygün A. (2021). Land application of municipal sewage sludge: Human health risk assessment of heavy metals, *Journal of Cleaner Production*, **319**, 128568.

Yang G., Zhang G. and Wang H. (2015). Current state of sludge production, management, treatment and disposal in China, *Water research*, **78**, 60-73.

Yang H. W., Wang J. G., Li C. *et al.* (2021). Engineering case study of municipal sludge drying and incineration technology application. *China Water & Wastewater*, **37**, 136-140.

Zeng Q., Tang N., Chen H. *et al.* (2020). Application research of municipal sludge treatment and disposal technology, In: IOP Conference Series: Earth and Environmental Science, IOP Publishing.

Zhang C., Yang X., Tan X. *et al.* (2022). Sewage sludge treatment technology under the requirement of carbon neutrality: Recent progress and perspectives, *Bioresource Technology*, **362**, 127853.

Zhang S. W. (2023). Key issues in the construction of intelligent perception system for sludge drying and incineration engineering. *Water Supply and Drainage*, **59**, 124-128.

Zhao S. Q., Duan N. N., Tan X. J. *et al.* (2024). Economic analysis of the "anaerobic digestion + land use" technological route for urban sewage sludge, *Environmental Engineering*, **42**, 1-13.

Zhen G., Lu X., Kato H. *et al.* (2017). Overview of pretreatment strategies for enhancing sewage sludge disintegration and subsequent anaerobic digestion: Current advances, full-scale application and future perspectives, *Renewable and Sustainable Energy Reviews*, **69**, 559-577.

Zheng G., Yu B., Wang Y. *et al.* (2021). Fate and biodegradation characteristics of triclocarban in wastewater treatment plants and sewage sludge composting processes and risk assessment after entering the ecological environment, *Journal of Hazardous Materials*, **412**, 125270.

Zhou H., Wei L., Wang D. *et al.* (2022). Environmental impacts and optimizing strategies of municipal sludge treatment and disposal routes in China based on life cycle analysis, *Environment International*, **166**, 107378.