Current Status and Trends of Municipal Sludge Treatment and Disposal in China

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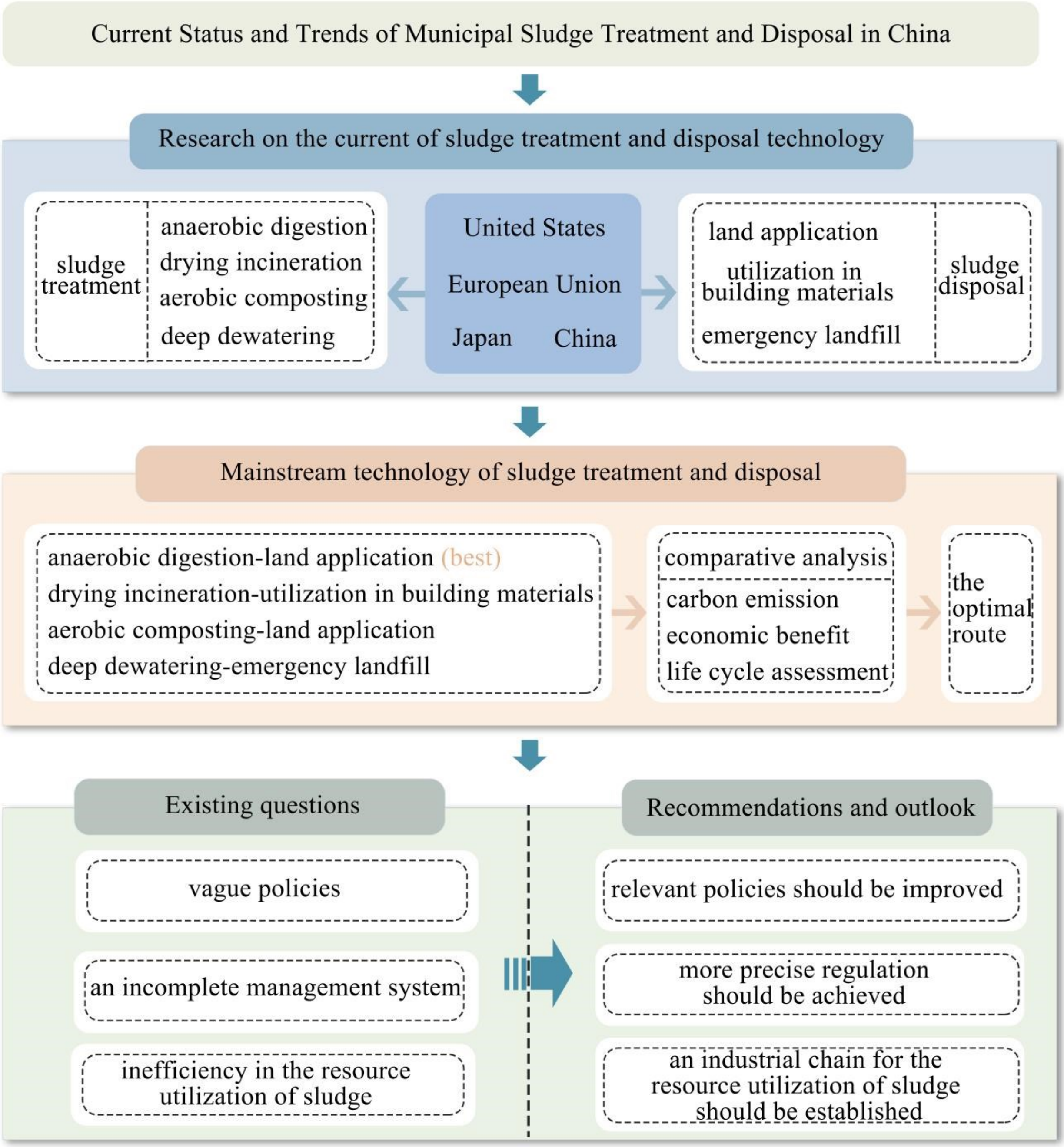
Graphical abstract



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 (-4.6×10^7MJ). 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

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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 line; 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.

1. 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.

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.,

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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).

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.

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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)

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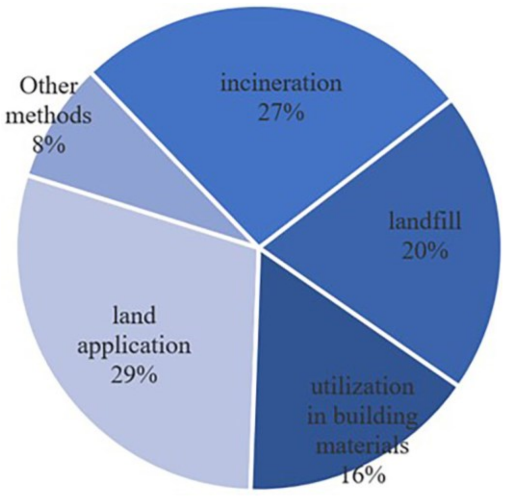

Figure 1. Proportion of Sludge Utilization and Disposal Methods in China, 2019

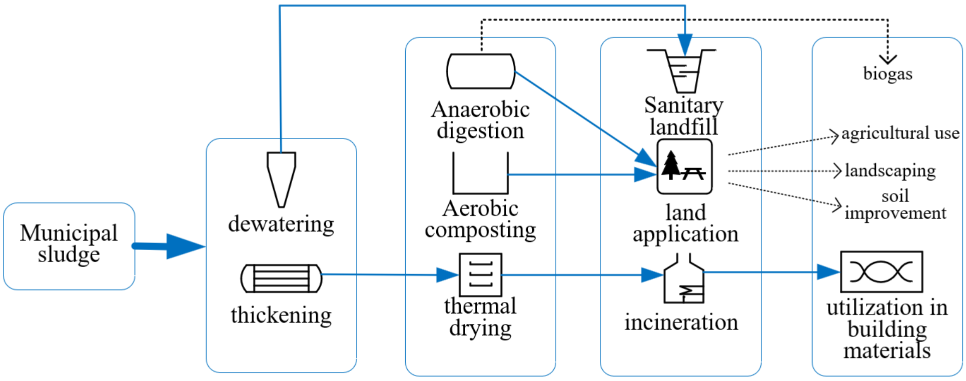

Figure 2. Mainstream Routes for Sludge Treatment and Disposal

1.1 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).

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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

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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).

1.2 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).

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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).

1.3 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

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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).

1.4 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.

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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.

1.5 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 $kg \cdot t^{-1}$),

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sanitary landfill (786.24 kg·t^{-1}), incineration (635.52 kg·t^{-1}), anaerobic digestion (371.4 kg·t^{-1}) and aerobic composting (614.17 kg·t^{-1}). The main carbon compensation methods include land application (-415.83 kg·t^{-1}) and building material utilization (-169.75 kg·t^{-1}). Taking a comprehensive view, the carbon emission of anaerobic digestion-land application is -44.43 kg·t^{-1}. Therefore, this technological route has greater carbon offset potential and better environmental friendliness.

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.

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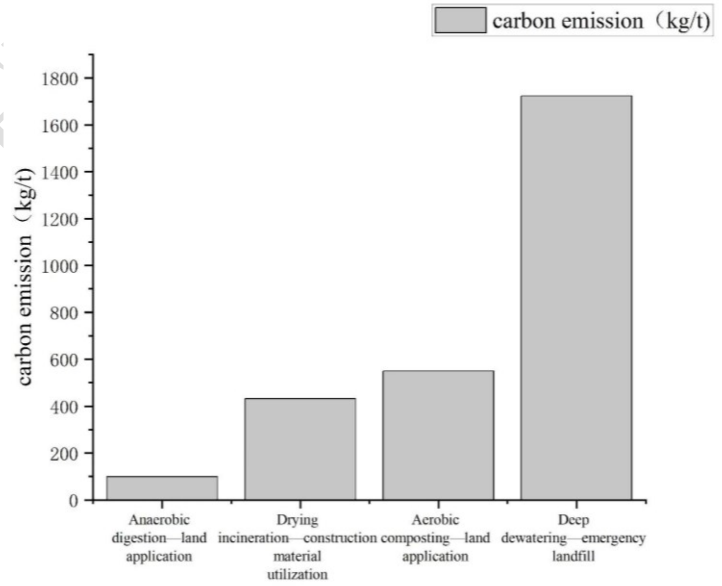

Figure 3. Carbon Emission Diagram of Mainstream Technologies for Sludge Treatment and Disposal

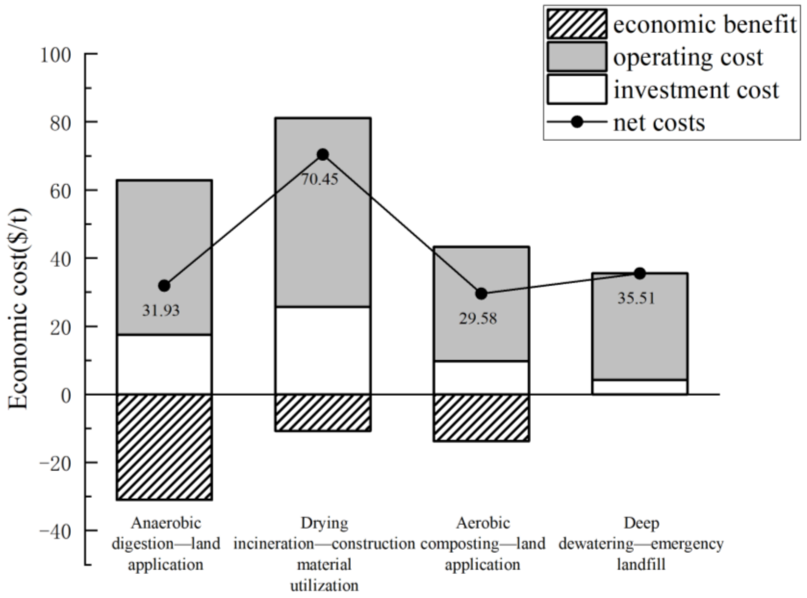

Figure 4. Economic Cost Diagram of Sludge Treatment and Disposal Routes

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 1.9×10^5 kg, save about 6.2×10^8 kWh of electricity consumption and about 4.6×10^7 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.

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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.

2. Problems Faced by Sludge Treatment and Disposal

2.1 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

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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.

2.2 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.

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2.3 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 making 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).

3. Recommendations and Outlook for Sludge Treatment and Disposal

3.1 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 provides 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

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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 provides solid financial support for the harmless treatment and resource utilization of sludge.

3.2 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.

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3.3 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.

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Tables and Figures

Table 1. Sludge Treatment Technologies

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

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

Figure 2. Mainstream Routes for Sludge Treatment and Disposal

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

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

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