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Safe Disposal and Resource Recovery of Urban Sewage Sludge in China

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Abstract: As a by-product of wastewater treatment, sludge is both a pollutant and a resource. Proper disposal of sludge is important for reducing pollution and carbon emissions during sewage treatment. Sludge management has transitioned from prioritizing wastewater treatment over sludge to focusing equally on treating wastewater and sludge in China, and the technologies and standards system have developed rapidly. However, against the background of carbon peaking and carbon neutrality, there remain shortcomings in sludge treatment in China. In this paper, we reviewed the current statuses of sludge treatment in China from the aspects of urban sludge production and characteristics, sludge treatment technologies, and policy and standards systems, and summarized the prominent problems associated with sludge treatment in terms of management system, technical standards, and route selection. Considering the development stage and international development trends, we propose a development concept of "green and low carbon, resource recycling, environmentally friendly, and adaptation to local conditions." Corresponding key measures are also proposed. Specifically, the top-level design should be strengthened to coordinate facility planning and layout, and treatment routes should be selected according to local conditions. The standards system and price subsidy mechanism for sludge treatment should be improved to clarify the division of responsibilities and strengthen the supervision mechanism. The integration level of the entire chain should be promoted by strengthening weaknesses to form a technology model that can be applied widely. Research on frontier technologies should be conducted to innovate and upgrade the technologies and equipment for sludge disposal and recycling.

Keywords: sewage sludge; sludge treatment; pollution control; resource recovery; reduction of pollution and carbon emissions

1 Introduction

As a product of the wastewater treatment process, sludge concentrates and collects 30%–50% of pollutants and organic matter in wastewater and is both a pollutant and resource. If not properly treated, it will cause serious environmental pollution and waste of resources [1]. Sludge is characterized by a high content of water and perishable organics. Thus, sludge reduction, stabilization, harmless and recycling treatment, and disposal is an important task of the battle against pollution, as well as the development direction of strategies to reduce pollution and carbon emissions in the sewage treatment industry.

In China, with the accelerating urbanization and improvement of wastewater treatment facilities, the scale of urban wastewater treatment has exceeded 2.2×10^8 t/d, and the resulting sludge production exceeds 6.6×10^7 t/a (based on an 80% moisture content). Because sludge treatment and disposal in China started relatively late, and

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there was a focus on wastewater treatment over sludge treatment, landfilling has been the main sludge disposal method for a long time. However, landfills cause serious secondary pollution, resource wastage and fugitive greenhouse gases emission, resulting in the emission reduction effect of sewage treatment being not as expected [2]. In recent years, with the social concerns regarding sludge, a series of standards and regulations, as well as relevant plans and policies, have been developed to gradually drive sludge management from being focused on wastewater treatment to both wastewater and sludge management.

The investment in technological innovation of sludge treatment technology and equipment has increased in recent years. During the 11th Five-Year Plan period, focus was placed on breaking down key technical barriers. During the 12th Five-Year Plan period, multiple technical routes were solidified, and the equipment industry realized from point to line development. During the 13th Five-Year Plan period, the entire technological chain was integrated and its application realized a from-line-to-surface type of breakthrough. Presently, four mainstream technical routes have been formed, and comprehensive demonstration areas for the entire sludge treatment and disposal chain have been built in Beijing and Shanghai. Different demonstration models have been built, such as an anaerobic digestion + land use (forest land) model represented by Beijing, a dry incineration + utilization as building materials model represented by Shanghai, an anaerobic co-digestion of sludge and food waste + garden utilization model represented by Zhenjiang, and an aerobic fermentation + land use (nutrient soil) model represented by Nanning and Zhengzhou [3].

However, it should be noted that the technological level of sludge treatment and disposal in China is still far behind the international level. As a shortcoming in sewage treatment, sludge treatment still needs to be strengthened. At the conceptual level, sludge treatment remains at the stage of reduction and harmlessness in China, whereas it has basically realized resource recycling in developed countries. At the technical level, sludge in China is characterized by large production, concentrated generation, a high sand content, and a low organic matter content, which differs significantly from that in developed countries. As a result, the introduction of foreign technology and equipment and mature technical routes encounter bottlenecks. At the management level, the standards system, management mechanism, and supporting measures of sludge treatment and disposal are inadequate. The sludge consumption path has not been completely developed. For example, landfills are unsustainable and land utilization is limited for sludge treatment [4].

Under the background of climate change and shortage of energy and resources, the right path for sludge treatment and disposal in China is to reduce secondary pollution risk via the harmless treatment and disposal of sludge, and to achieve synergistic reductions in pollution and carbon emissions by reinforcing resource utilization of sludge. This is of great importance in terms of pollution prevention and control, ecological civilization construction, and achieving carbon peaking and carbon neutrality goals. This paper summarizes the overall situation of sludge treatment and disposal in China, analyzes the prominent problems faced during sludge treatment and disposal and resources recovery, and proposes development ideas and suggestions, to provide a reference for technology and management research of sludge treatment and disposal.

2 Overall situation of urban sludge treatment and disposal in China

2.1 Sludge production is large and centralized and the sludge is of poor quality and difficult to treat

The urbanization level and sewage treatment capacity has increased rapidly in China, and the resulting sludge production has increased dramatically. According to the *2020 Statistical Yearbook of Urban and Rural Construction*, the dry municipal sludge production of wastewater treatment plants (WWTPs) in cities above the prefecture level was 1.163×10^7 t and 1.7×10^6 t in county-level cities in 2020. Based on an 80% moisture content, the wet sludge production of cities at the county level and above is 6.664×10^7 t (Fig. 1) [5]. It is reasonably expected that China's sludge production will exceed 8×10^7 t in 2025. The scale of WWTPs is generally small and medium in developed countries, while being mainly centralized in China, and the average scale of WWTP is 10 times of that in developed countries. Sludge production is relatively centralized in China, and the demand for reduction has become more urgent. Moreover, higher requirements have been proposed for sludge land use and incineration flue gas treatment due to the limited environmental capacity, resulting in higher pressures concerning the safe treatment and disposal of sludge.

Sewer network construction in China is incomplete, and the influent from WWTPs contains a large amount of microfine sand. The efficiency of grit removal is low, and the primary settling tanks are cancelled in some WWTPs due to an insufficient carbon source, leading to an accumulation of microfine sand in sludge. In southern China, in particular, sludge generally has the characteristics of a low organic matter and high sand content. The

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organic matter content (30%–60%) of sludge from sewage plants in China is generally lower than that in developed countries (60%–80%) [6]. The low organic matter of sludge directly affects the efficiency of anaerobic digestion and the energy consumption of incineration systems, making sludge treatment and disposal more challenging. Presently, landfilling remains the main method of sludge disposal in China, and the phenomenon of random disposal and landfill is relatively common in some cities. Nationally, more than 50% of sewage sludge is disposed of by simple landfilling, leading to a high risk of secondary pollution. Compared with wastewater treatment, the treatment and disposal of sludge in China faces a more serious challenge.

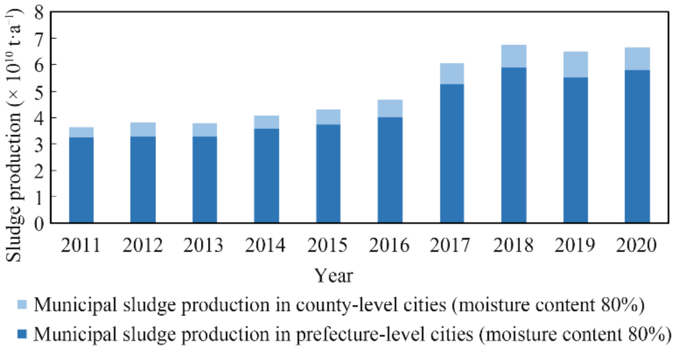

Fig. 1. Changes of sludge production from wastewater treatment plants in China.

2.2 Technologies of sludge treatment and disposal have developed rapidly, and mainstream technical routes have been formed

Sludge treatment in China started in the period of the 10th Five-Year Plan. Since the 11th Five-Year Plan period, the country has paid considerable attention to sludge treatment and invested in a lot of resources, and the key technology of sludge treatment and disposal has achieved a breakthrough of “grow out of nothing.” During the 12th Five-Year Plan period, the technologies and equipment of sludge treatment and disposal developed rapidly, and the technical system suitable for national conditions has achieved a breakthrough of “from point to line.” During the 13th Five-Year Plan period, the chain integration and engineering verification of sludge treatment and disposal technology routes were fully conducted at the levels of technology, standard, and policy, and a breakthrough of “from line to surface” was achieved. Presently, we have basically built a sludge treatment and disposal and resource utilization technical system that is adapted to local conditions, diverse and co-existing, and matched with the characteristics of China’s sludge quality. Four mainstream technical routes for safe sludge treatment and disposal and resource utilization have been formed: anaerobic digestion + land utilization, aerobic fermentation + land utilization, dry incineration + landfill or building materials utilization, and deep dewatering + temporary landfill (Fig. 2) [7].

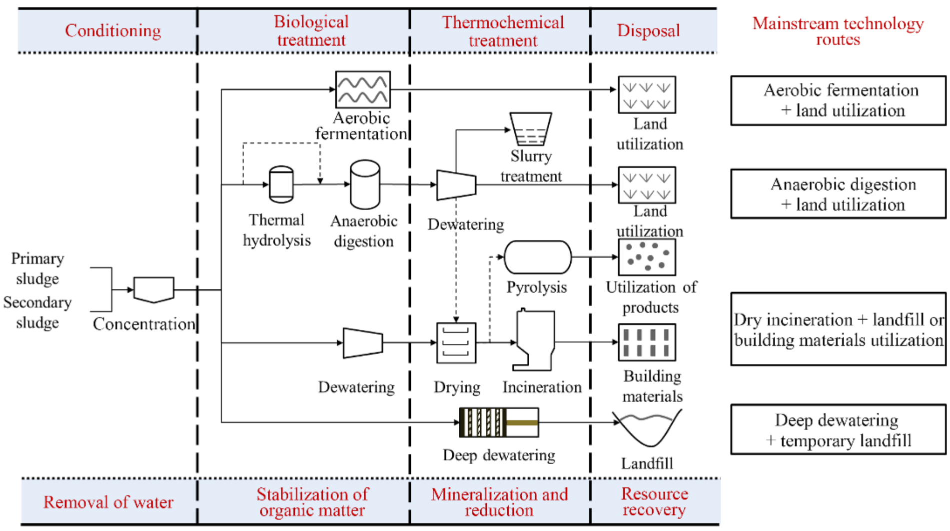

Fig. 2. Mainstream technical routes of sludge treatment and disposal in China.

A series of breakthroughs in key technologies and major equipment have been made in sludge biological treatment and stabilization, dewatering and reduction, thermochemical treatment and secondary pollution control, resource utilization of end-product, and other processes. Aiming at solving the problems of low organic matter content, low organics conversion rate, low organic load, and low engineering benefits, advanced anaerobic digestion technologies, such as thermal hydrolysis pretreatment, high solids anaerobic digestion, anaerobic co-digestion of sludge and food waste, have been developed, forming an advanced anaerobic co-digestion technology system suitable for the sludge characteristics in China. Regarding the common problems of conventional aerobic fermentation, such as long fermentation cycles and difficult odor control, intelligent aerobic fermentation, drum dynamic high-temperature aerobic fermentation, and other technical equipment have been developed. Regarding the bottleneck problems of complex moisture distribution in sludge, difficult deep dewatering, and high energy consumption, new technical equipment, such as high-pressure diaphragm plate filter press dewatering, and low-temperature vacuum dewatering and drying, have been developed. Regarding the problems of high energy consumption, complex control, and a lack of large-scale equipment for sludge thermochemical treatment, key technologies and equipment, such as disc and paddle drying, fluidized bed self-sustaining incineration, and co-disposal in cement kiln, have been developed. Aiming at solving the bottleneck of disposal outlet of sludge treatment products, key technologies, such as landscape utilization and soil improvement of sludge stabilization products, as well as utilization of incineration ash for building materials, have been developed, which has provided technical support for solving the sludge problem.

China has built and operated a batch of sludge treatment demonstration projects. Typical sludge anaerobic digestion projects include Sludge Anaerobic Digestion Project in Shanghai Bailongang Sewage Treatment Plant (1020 t/d; 80% moisture content, the same below), Changsha Sewage Treatment Plant Sludge Centralized Disposal Project (500 t/d), Zhenjiang Food Waste and Sludge Co-Treatment Project (260 t/d), Xi'an Sewage Treatment Plant Sludge Centralized Disposal Project (1000 t/d), and Five sludge treatment centers in Beijing: Gaobeidian, Xiaohongmen, Huaifang, Qinghe, and Gaoantun (total scale of 6128 t/d), etc. Typical sludge aerobic fermentation projects include Zhengzhou Bagang Sludge Treatment Project (600 t/d) and Zhengzhou Shuangqiao Sludge Treatment Project (600 t/d). Representative sludge drying incineration projects include Shanghai Shidongkou Sludge Drying Incineration Project (360 t/d) and Zhuyuan Sludge Drying Incineration Project (750 t/d).

From a comprehensive view, China has initially formed three whole chains and cross-industry sludge treatment and disposal modes, namely "advanced anaerobic digestion + gardening/land use," represented by Beijing, Changsha, and Zhenjiang; "aerobic fermentation + gardening/land use," represented by Nanning, Zhengzhou, and Chongqing; and "dry incineration + ash landfill/building material use," represented by Shanghai, thereby establishing an important foundation for improving the entire chain of sludge treatment and disposal technology systems.

2.3 Management policy and standards system of sludge treatment and disposal have taken shape

In terms of management policies, management started to focus on the sludge issue in 2012 and successively issued policy documents on sludge treatment and disposal. Since 2015, the sludge treatment and disposal industry has entered a period of rapid development. For example, the *Water Pollution Prevention and Control Action Plan* presents the requirement that sludge generated by wastewater treatment facilities should be stabilized, harmless, and recycled for treatment and disposal. The *Management Measures for the Collection and Use of Sewage Treatment Fees* clearly incorporates sludge treatment costs into sewage treatment fees. The *13th Five-Year Plan for the Construction of National Urban Sewage Treatment and Recycling Facilities (2017)* states that sludge treatment and disposal in China has entered a development stage of "equal emphasis on sludge and wastewater treatment." The *Implementation Plan for Strengthening Weaknesses of Urban Domestic Sewage Treatment Facilities (2020)* emphasizes the promotion of harmless disposal and resource utilization of sludge. The *14th Five-Year Plan for the Development of Urban Sewage Treatment and Resource Utilization (2021)* proposes to fully realize the harmless and resource-based disposal of sludge by 2035. The *Implementation Plan for Synergizing Reduction of Pollution and Carbon Emissions (2022)* calls for the improvement of sludge disposal and comprehensive utilization.

In recent years, sludge standards, including basic standards, sludge quality standards, sludge testing standards, technical regulations, operation and management guidelines, and product standards, have been developed and issued. (1) In terms of technical guidelines, the *Technical Policy on Sludge Treatment and Disposal and Pollution Prevention in Urban Sewage Treatment Plants (trial implementation)*, the *Best Feasible Technology Guide on*

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Sludge Treatment and Disposal and Pollution Prevention in Urban Sewage Treatment Plants (trial implementation), the *Technical Guide on Sludge Treatment and Disposal in Urban Sewage Treatment Plants (trial implementation)*, and others have clarified the mainstream technical routes for sludge treatment and disposal and provided policy support for solving the sludge problem. (2) In terms of sludge quality standards, a series of national and urban construction standards have been issued (Table 1), providing a technical basis for land use, building material utilization, incineration, landfilling, and other processes. (3) To ensure the standardization and normalization of sludge treatment technology, the standard regulations covering mainstream sludge treatment technology have been issued. These include the *Technical Protocol for Anaerobic Digestion of Sludge in Urban Sewage Treatment Plants (T/CECS 496—2017), Technical Protocol for Aerobic Fermentation of Sludge in Urban Sewage Treatment Plants (T/CECS 536—2018), Technical Protocol for Dry Incineration of Urban Sewage Sludge in Fluidized Beds (CECS 250—2008), and Technical Protocol for Deep Dewatering of Sludge in Urban Sewage Treatment Plants by Diaphragm Filtering (T/CECS 537—2018)* [8]. (4) To guide the process design of mainstream technologies and improve the level of engineering operation, several guidelines were issued, including the *Guidelines for Design and Operation Management of Sludge Deep Dewatering Processes in Urban Wastewater Treatment Plants (T/CECS 20005—2021), Guidelines for Design and Operation Management of Sludge Aerobic Fermentation Processes in Urban Wastewater Treatment Plants (T/CECS 20006—2021), Urban Wastewater Treatment Plant Sewage Sludge Anaerobic Digestion Process Design and Operation Management Guide (T/CECS 20007—2021), Urban Wastewater Treatment Plant Sludge Drying Incineration Process (T/CECS 20008—2021), Design and Operation Management Guide of Sludge Drying and Incineration Process in Urban Wastewater Treatment Plants (T/CECS 20007-2021)*, and *Design and Operation Management Guide of Sludge Drying and Incineration Process in Urban Wastewater Treatment Plants Guide to Garden Utilization of Sludge Treatment Products from Urban Wastewater Treatment Plants (T/CECS 20009-2021) CECS 20009-2021)*.

Overall, the technical level of sludge treatment and disposal and resource recovery has been comprehensively improved; meanwhile, the standard specifications have been compiled, and a standards system covering sludge treatment and disposal was initially built. In terms of treatment, it covers the technical routes of anaerobic digestion, aerobic fermentation, drying incineration, and deep dewatering. In terms of disposal, it covers the key directions of land use and building materials utilization. From the aspect of technological application, it covers design, construction, operation, and management, thereby providing basic support for the normative application and promotion of technological achievements.

Table 1. Main disposal methods and standards of sludge in China.

Disposal method		Standard number	Standard Title
Land use	Agricultural use	GB4284—2018	*Control standards of pollutants in sludge for agricultural use*
	Landscaping	GB/T23486—2009	*Disposal of sludge from municipal wastewater treatment plant—quality of sludge used in gardens or parks*
	Soil improvement	GB/T 24600—2009	*Disposal of sludge from municipal wastewater treatment plant—quality of sludge used in land improvement*
	Forest land use	CJ/T 362—2011	*Disposal of sludge from municipal wastewater treatment plant—quality of sludge used in forestland*
Building materials utilization	Brickmaking	GB/T25031—2010	*Disposal of sludge from municipal wastewater treatment plant—quality of sludge used in making brick*
	Cement clinker	CJ/T 314—2009	*Disposal of sludge from municipal wastewater treatment plant—quality of sludge used in the production of cement clinker*
Incineration	Independent incineration	GB/T 24602—2009	*Disposal of sludge from municipal wastewater treatment plant—quality of sludge used in separate incineration*
Landfill	Mixed landfill	GBT 23485—2009	*Disposal of sludge from municipal wastewater treatment plant—quality of sludge for co-landfilling*

3 Problems of urban sludge treatment and disposal in China

3.1 Top-level design needs to be supplemented, and the management standards system is incomplete

The top-level design of sludge treatment and disposal is lacking, the management mechanism coordinated by multi-departments is not sound. Some regions place emphasis on wastewater treatment over sludge treatment and fail to consider the sewage and sludge treatment facilities simultaneously. The capital investment in sludge treatment and disposal is relatively insufficient, usually only accounting for 10%–20% of the total investment in

WWTP, which is far lower than the average level of 30%–50% in developed countries, resulting in a limited capacity of sludge treatment facilities. For example, some areas rely on coal-fired power plants for co-disposal and lack independent sludge treatment facilities [9].

The policy and standard systems for sludge lack a reasonable supervision and assessment mechanism, which need to be improved. Most of the existing standard and specification documents are recommendatory (or qualitative) requirements at the macroscopic level, which are not systematic and cohesive. There are no supporting implementation rules and safeguard measures, and the operability is poor. This affects the management level of sludge treatment and is not conducive to a healthy development of the sludge treatment and disposal industry [9].

Sludge treatment and disposal management involves housing and urban–rural development, ecology and environment, agriculture, forestry, and other management departments. There is no clear solution regarding the final disposal of sludge, the cross-sectoral, cross-industry, and cross-regional collaboration mechanism is still missing, and sludge treatment products face the dilemma of having nowhere to go. Although the *Sewage Treatment Fee Collection and Use Management Measures* and *Water Pollution Prevention and Control Law* both clearly proposed that the cost of sludge disposal should be included in the cost of sewage treatment, the price mechanism for sludge treatment and disposal is still missing.

3.2 Poor sludge quality and low level of stabilization and harmlessness

Wastewater treatment aims to degrade and remove pollutants, and 30%–50% of pollutants in wastewater are transferred into sludge; therefore, sludge stabilization treatment can be regarded as a continuation of pollutant degradation in the wastewater treatment process. It has become an international consensus that stabilization is an important part of sludge treatment. Anaerobic digestion is a common sludge stabilization process, which can reduce the secondary pollution risk during the disposal process and recover biomass energy of biogas, while realizing stabilization and sanitary treatment. All countries have mandatory requirements for sludge stabilization, and developed countries further stipulate that the sludge must be stabilized even if it is disposed of in a landfill. In Germany and Japan, even though sludge treatment in domestic wastewater treatment plant has adopted the route of incineration, anaerobic stabilization of sludge is also required before incineration. In the early 1990s, it established relevant requirements for sludge stabilization; however, these failed to be effectively implemented. Most sewage treatment plants have only completed the preliminary reduction of sludge, but have not performed stabilization and harmless treatment and disposal, which has potential risks of secondary pollution.

In developed countries, biomass energy recovered through sludge anaerobic digestion can meet 60% of the energy requirements of WWTPs. In China, the low organic matter content of sludge leads to low gas production and no considerable cost benefit. Nearly 2/3 of the sludge anaerobic digestion facilities constructed during the early stage have been shut down.

Some operation and management departments have a cognitive bias on the stabilization function of sludge anaerobic digestion and only measure the benefits of anaerobic system by the amount of biogas recovery, ignoring the value of stabilization treatment of perishable organic matter in sludge. As a result, the application ratio of anaerobic digestion processes is less than 5%, which is far below the international level, and it has become a short link in the entire chain of sludge treatment and disposal [11].

3.3 Obstructed sludge recycling disposal and unclear choice of technical route

It has long emphasized on sludge treatment, not disposal, leading to unclear technical route in China. The methods of sludge disposal mainly include landfilling, building materials utilization, and land utilization. (1) Sludge landfill will occupy a large area of land resources, cause secondary pollution and resource wastage, and greenhouse gases emission. In some economically developed areas, there is even no land for landfill. Therefore, landfilling is only a temporary and transitional technical route, which does not meet with the construction concept of "waste-free cities" and the development trend. (2) The utilization of sludge as building materials usually requires dry incineration or co-incineration of sludge to realize sludge mineralization and harmlessness. Due to the high moisture content of sludge, dry incineration systems have high energy consumption requirements, high operation costs, strict exhaust gas emission requirements (may produce dioxins and other pollutants), high pollution control costs, and a considerable neighborhood avoidance effect. Presently, there is no subsidy policy for building materials utilization of sludge incineration ash; therefore, the common method of ash disposal is landfilling, and the corresponding resource utilization level is low. (3) Land use is the most common way of sludge disposal in United States and European countries, where the proportion of land use exceeds 70%. However, sludge

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land use is obstructed in China [12]. The reasons for this are as follows: the sludge stabilization and harmless level of sewage treatment plant is low, which cannot meet the requirements of land use. Even if sewage sludge in some areas have realized stabilization treatment, they still face cross-sector and cross-industry barriers due to the gap in cognition and the lack of policy standards. In addition, there is a certain risk of heavy metals and other pollutants being present in sludge due to municipal sewage being mixed with industrial wastewater.

Although four mainstream technical routes for sludge treatment and disposal have been formed in China, and a batch of demonstration projects have been built and operated since the 12th Five-Year Plan period, the application of key technological achievements in demonstration projects lacks a systematic summary, and a comprehensive techno-economic assessment also need to be performed. There is an imbalance in the level of economic and social development in different regions of China, and the costs of different sludge treatment and disposal technical routes differ significantly, resulting in uncertainty and blindness in the selection of technical routes in different regions.

4 Development strategy for urban sludge treatment and disposal in China

4.1 Development concept

Establishing a systematic view of sewage and sludge treatment, as well as considering safe sludge treatment and disposal, are presently key tasks in the field of urban water pollution control. Efforts should also be made to follow the basic principles of “conducting overall planning, combining long-term and short-term considerations, adjusting measures to local conditions, ensuring regional coordination, achieving stability and reliability, utilizing green and low-carbon methods, and dominating by government under market operation,” as well as to build the harmless and resource utilization system of sludge, thereby achieving the comprehensive goal of reducing pollution and carbon emissions, supporting the construction of ecological civilization, and promoting high-quality development. Based on the national development stage, it is proposed to refer to the international development trend and to adopt the development concept of “green and low-carbon, resource recycling, environment-friendly, and localized.” By referring to the principle of “stabilization, reduction, harmlessness, and resource utilization,” which has become the international consensus on sludge treatment, taking harmlessness as the goal and resource recovery as the means, it is proposed to break through the technical and management bottlenecks of sludge treatment and disposal and promote the healthy development of the industry (Fig. 3).

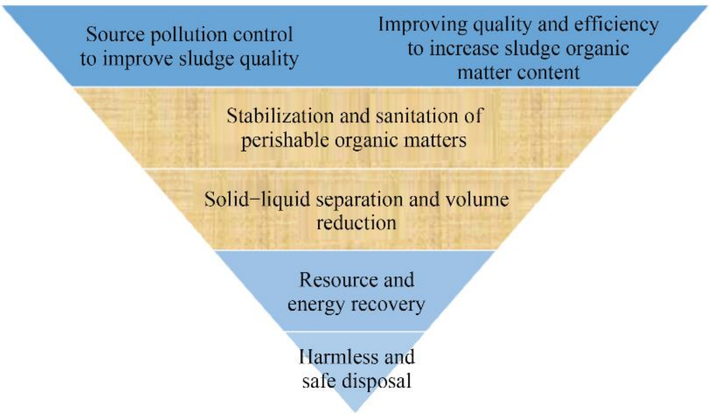

Fig. 3. “Inverted pyramid” principle of sludge treatment and disposal.

In terms of green and low-carbon, the strategy encourages the use of green and low-carbon treatment technologies and a reduction in the use of chemical agents to achieve energy saving and consumption reduction. It promotes green and efficient dewatering, anaerobic digestion, pyrolysis carbonization, and other technological routes to steadily reduce carbon emissions.

In terms of resource recycling, it highlights the resource attributes of sludge and strengthens the recycling of energy, carbon, nitrogen, phosphorus, and other resources in sludge; it supports the land use of sludge stabilization products and building materials utilization of incineration products to achieve a higher level of resource recycling.

In terms of environmental friendliness, it highlights the implementation of source reduction, pollution control, and strengthens the stabilization of perishable organic matters in sludge, sanitization of pathogenic bacteria, and other treatment. Attention should be paid to the safe disposal and resource utilization of end-products, and the scale of sludge landfilling should be gradually reduced.

In terms of localization, according to the sludge quality, production, distribution characteristics, combined with regional natural geographical conditions, environmental carrying capacity, long-term environmental benefits, local economic and technical level, and other factors, the appropriate path of sludge treatment and disposal should be clarified.

4.2 Key measures

4.2.1 Strengthening the top-level design to coordinate the planning and layout of facilities and choose the treatment and disposal routes according to local conditions

It is recommended to attach great importance to the sludge problem and raise the sludge treatment and disposal to the level of national ecological civilization construction. Attention should be paid to the top-level design, the layout of sludge treatment and disposal facilities should be planned rationally, and sludge treatment and disposal facilities should be incorporated into the construction planning of sewage treatment facilities. During the construction, reconstruction, and expansion of sewage treatment facilities, sludge treatment facilities should be planned, constructed, and put into operation simultaneously.

The quality of sewage treatment plant influent directly affects the sludge quality; thus, it is necessary to strengthen the construction of sewage networks and control the level of source pollutants to gradually improve the sludge quality. National space planning should be coordinated, planning and implementation should be done in stages based on the actual situation, equal emphasis should be placed on both sludge and water treatment, long-term and short-term should be considered simultaneously, and in-situ treatment and regional coordination should be performed. The sludge safety disposal and resource recovery management system should be improved, supervision capacity of the entire process of sludge treatment and disposal should be enhanced to ensure the safety and recycling of sludge resources.

Considering the sludge quality and quantity comprehensively, combined with the level of regional economic and social development, the sludge treatment and disposal method should be selected according to local conditions to ensure economically rational, low energy consumption, and low carbon emissions. The sludge yield and disposal methods should be comprehensively sorted out, in-plant reduction and stabilization should be implemented, treatment and disposal facilities with low treatment level, unstable operation state, and high risks of secondary pollution should be gradually eliminated. The integrated treatment of sludge and food waste, restaurant waste, manure, and other urban and rural organic wastes should be explored to realize a synergistic disposal effect [13].

4.2.2 Improving the standards system, price subsidy mechanism, and responsibility division and supervision mechanisms for sludge treatment and disposal

The development or revision of standards for land use, dry incineration, anaerobic digestion, and collaborative treatment and disposal of sludge should be performed in a timely manner. The implementation rules and regulations should be improved, and sludge land use specifications and standards that adapt to the national conditions and have strong operability should be established. The standards system of harmless treatment and resource utilization of sludge should be improved. Certification of resource-based products should be encouraged, standards for sludge resource-based testing and product certification should be developed, and certification and credit mechanisms at the government, industry, and social levels should be established to guarantee the market outlets for sludge resource-based products. It is also recommended to make the best use of the ongoing circumstances. According to their own land resources, sludge quality, economic and social development conditions, and other factors, local governments are encouraged to develop a batch of local sludge treatment and disposal standards based on national standards.

The price subsidy mechanism of sludge treatment and disposal, as well as resource recovery, should be improved in a timely manner. The sludge treatment fee can be set according to the principle of covering the normal operation of the sludge treatment facility and the cost of sludge disposal and making a reasonable profit. The cost should be adjusted dynamically according to the local pollution prevention objectives, considering factors such as the upgrading of sewage discharge standards and possible increases in the cost of sludge disposal. A market-based pricing mechanism for sludge resource utilization should be explored. The development of incentives for land use of sludge products, especially policies for integrated sludge use in forestry and agriculture (non-food chain), should be studied. For sludge products, the charging mechanism should be adjusted, the tax policy should be improved, and support should be provided for sludge incineration, cement kiln co-incineration, cogeneration of heat and power, biomass energy generation, and biogas supply.

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The government should play a leading role, and the allocation of resources should be decided by the market, thus to strengthen the supervision mechanism of sludge treatment and disposal. The management department should establish a regulatory mechanism and pay attention to long-term effectiveness, to promote the implementation of responsibilities of the responsible parties of each link. The relationship between the responsible parties of each link should be determined, and a cross-sectoral coordination mechanism should be established. The environmental protection department is responsible for environmental supervision, strengthening the source control of urban sewage treatment plants, and promoting the improvement of sludge quality. The agriculture and gardening departments are responsible for promoting the smooth entry of sludge stabilization products into land use. The development and reform department is responsible for formulating policies on incentives, investment and costs of sludge resources, and energy recovery. The sludge treatment and disposal facility operating enterprises are responsible for the safe disposal of sludge.

4.2.3 Strengthening the weaknesses, improving the integration level of the entire chain, and forming a technical model that can be promoted

The shortcomings regarding sludge stabilization treatment should be overcome. Sludge stabilization treatment is an important part of the sewage treatment process; thus, sludge anaerobic or aerobic stabilization facilities should be built simultaneously in the newly built or expanded sewage plants, and the reconstruction of sewage plants should consider adding sludge stabilization treatment facilities.

The method of sludge resource disposal and utilization should be broadened. According to the basic requirements of being safe, environmentally friendly, sound, and reliable, the actual situation of a region should be considered, suitable technical paths and market mechanisms should be selected, and a sludge resource utilization model should be established with the consideration of various complementary paths, such as energy and material recycling, land use, and building material utilization. The recycling of organic matter and nutrient resources should be encouraged after the aerobic fermentation or anaerobic digestion of municipal sludge. Land use should be actively promoted according to national and local standards and regulations, priority should be given for sludge products that meet the requirements of soil improvement, landscaping, and non-edible agriculture. For areas with scarce land resources, high land use cost, and excessive heavy metal content, it is encouraged to use sludge ash for building materials after incineration. The technical path of phosphorus recovery from sludge incineration ash should be explored.

In view of the differences in economic development level, sludge characteristics, and land use conditions in different regions, there is a trend of multiple routes for sludge treatment and disposal in the future. Therefore, technical routes should be selected according to local conditions: (1) The technical route of sludge (advanced) anaerobic digestion is suitable for areas with abundant land resources and good land consumption conditions. For the sludge with a low organic matter content, the technical route of "anaerobic co-digestion with food waste/manure + land use" is encouraged. (2) The technical route of sludge aerobic fermentation is suitable for areas with low population densities, abundant land resources, and good land consumption conditions, and has a good prospect for application in economically less developed areas. (3) The technical route of sludge dry incineration is suitable for economically developed, densely populated areas with high land costs, or areas where sludge treatment products do not have the conditions required for land consumption. (4) The technical route of "sludge deep dewatering + sanitary landfill" is only applicable to emergency treatment situations or areas with local landfill conditions and limited economic conditions.

A batch of mature and applicable processes, technologies, and equipment should be promoted, the industrialization system of urban sludge resource and energy utilization technology should be enhanced, improvement of the entire chain capacity of sludge treatment and disposal, including technology, equipment, industry and management, should be promoted, to support the healthy development of circular economy.

4.2.4 Making breakthroughs in frontier technology research, to upgrade sludge treatment technologies and equipment

In the context of coping with global climate change and energy resource shortage, the efficient recovery of energy and recycling of resource materials in sludge has become an international research hotspot and also an important component for the future transformation of wastewater treatment plants from "pollutant removal" to "energy and resource factories" [14]. It is recommended to increase investments in scientific and technological research and development, support the policy of new technology development, and focus on strengthening the basic theoretical research and technology and equipment development for sludge treatment and disposal and resource utilization. By relying on the technological progress of molecular biology, new materials, big data, Internet of Things, intelligent perception, artificial intelligence, and other technologies, the innovation and upgrading of the technical system of sludge treatment and disposal and recycling can be realized, and a refined, efficient, and intelligent level of sludge treatment technology can be comprehensively improved.

With the goal of "carbon peaking and carbon neutrality," there is an urgent need for a batch of future-oriented new principles, technologies, and methods of sludge treatment and disposal and resource recovery, to effectively enhance China's frontier technology reserve capacity in this field (Fig. 4). (1) In terms of basic research, based on the pollution and resource properties of sludge, studies should be conducted on the multi-media and multi-component interaction mechanism of sludge [15]. New wastewater treatment processes should be developed to promote sludge quality and quantity reduction. The transformation mechanism and regulation principle of high value-added products and nutrients recovery should be analyzed. The thermodynamic mechanism of sludge thermochemical transformation process, migration and transformation of pollutants, and the environmental behavior of persistent organic substances should be clarified, and a regulation principle and method should be proposed to reduce toxic and harmful substances in end products. (2) In terms of the development of key technologies, aiming at the low conversion rate of sludge anaerobic digestion, new technologies such as novel sludge pretreatment, enhanced bioconversion with exogenous addition, and highly efficient anaerobic reactors should be broken through. The application of advanced anaerobic digestion technologies, such as those with a high solid content and co-digestion, should be strengthened to achieve efficient and stable recovery of biomass energy [16]. New technologies should be developed for efficient recovery of carbon, nitrogen, phosphorus, and other resources in sludge to achieve recycling of resources. Environment-friendly dewatering chemicals and efficient conditioning technology should be developed to reduce the energy and material consumption level of sludge solid–liquid separation [17]. For sludge drying and incineration, the energy optimization between drying and incineration system should be strengthened, coupling with anaerobic digestion technology should be considered to improve the energy level of the system, and building materials utilization and extraction of phosphorus resources should be conducted for incineration ash.

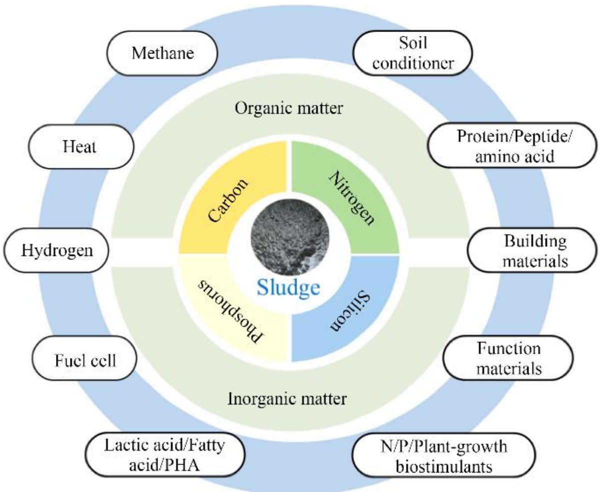

Fig. 4. Hot topics on sludge treatment and resource recovery.

Notes: PHA means polyhydroxyalkanoate; N/P refers to nitrogen and phosphorus

5 Conclusion

After the implementation of the three Five-Year Plans, China has initially built a technical system for sludge treatment and disposal and resource utilization that is adapted to local conditions, diverse, and compatible with the characteristics of the sludge, as well as developed a related standard system, formed four mainstream technical routes for sludge treatment and disposal, and built a batch of demonstration projects. However, compared with the requirements of ecological civilization construction and high-quality development of the urban sewage treatment industry, there is still a large gap in sludge treatment and disposal and resource utilization

Under the background of carbon peaking and carbon neutrality, sludge treatment and disposal in China should follow the development concept of "green and low-carbon, resource recycling, environment-friendly, and localized." We should learn from the principle of "stabilization, reduction, harmlessness, and recycling," which

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has become an international consensus of sludge treatment. We should strengthen the top-level design and overall planning of facilities, taking harmlessness as the goal and resource recovery as the means, to promote a healthy development of the sludge treatment industry. We should gradually improve the policy standard system and price subsidy policy, strengthen the division of responsibility and supervision mechanism, and form a system of safe treatment and disposal and resource utilization with complete chains. We should make up for the shortcomings of sludge stabilization treatment, promote the construction of sludge treatment facilities, broaden the path of sludge resource recovery, and select treatment technology routes according to local conditions. Regarding the future demand of sludge treatment and disposal and resource recovery, we should make breakthroughs in developing a batch of new technologies, such as sludge efficient anaerobic digestion, new sludge dewatering, and sludge pyrolysis carbonization, and promote green and low-carbon treatment technologies, thus providing support for the goal of reducing pollution and carbon emissions in the sewage treatment industry.

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