Technical and Economic Feasibility of Different Urban Sludge Treatment Technologies

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***Abstract*—Currently, the level of urban sewage treatment technology in China is very mature, but the development of urban sludge technology lags behind. In some cities, sludge has not been effectively treated for a long time, emitting foul odors that seriously affect people's daily lives. Moreover, heavy metals and pathogens cause corrosion and damage to the land. Therefore, it is particularly important to choose an efficient and environmentally friendly approach to urban sludge treatment. This article lists three routes for urban sludge treatment. The Ebsilon software was used to simulate the co-combustion process of coal and sludge in the sludge incineration route. Based on domestic and international research results, the technical characteristics of sludge pyrolysis and composting were analyzed. The research method of comparative analysis was adopted to comprehensively compare and analyze the technical characteristics and return on investment (ROI) of the three routes. This research method can intuitively demonstrate the advantages and disadvantages of the three routes, and accurately and quantitatively determine the best route. In conclusion, Route 1: the comprehensive treatment process of drying and incineration is currently the most suitable route for China's development prospects. It has the most mature technology and the widest range of applications, achieving the highest efficiency in sludge treatment. In the foreseeable future, sludge incineration technology will remain the cornerstone of sludge treatment and disposal in China.**

***Keywords*—sludge incineration, sludge pyrolysis, sludge composting, technical analysis, economic analysis**

I. INTRODUCTION

In recent years, the sludge production in China has been gradually increasing. Sludge can be divided into three main types: urban sewage sludge, wastewater treatment plant sludge, and industrial sludge [1]. Among them, urban sewage sludge accounts for the largest proportion, requiring the most investment for treatment, and causing the most severe environmental pollution. The promulgation of regulatory documents related to sludge treatment and disposal in China was relatively late, with 2007 as a dividing line. The sludge treatment and disposal process in China can be divided into two stages: the initial stage from 1984 to 2007 and the development stage after 2008 [2] .The overall goal of the "14th Five-Year Plan for the Development of Urban Sewage Treatment and Resource Utilization" issued by the National Development and Reform Commission from 2017 to 2021 is to "further improve the harmless and resource utilization level of sludge in cities and counties, with a sludge harmless treatment rate of over 90%." By 2035, the plan aims to "fully achieve the harmless treatment of sludge, with significantly improved efficiency in sludge resource utilization" [3].

With the increasing emphasis on environmental protection by the country, the resource utilization of urban sludge has attracted the attention of many scholars. In the paper by Wang [4], the properties and quality of sludge in a city in southwest China were studied and analyzed. Two disposal methods were proposed: bio-leaching + plate-frame dewatering + aerobic fermentation + land utilization, and bio-leaching + plate-frame dewatering + cement kiln co-disposal. In the paper by Liu [5], taking a city in northern China as an example, a systematic research on the urban sludge treatment and disposal system was conducted at the level of sewage special planning. A diversified sludge treatment and disposal network of "4 + n + 1" was constructed, achieving the coordinated treatment of sludge and water and the intensive utilization of land. Wang [6] analyzed the impact of sludge composting as a substitute for chemical fertilizers on soil and crop nutrients, specifically its effect on crop yield and the risk of heavy metal pollution in soil after sludge composting. Feng [7] utilized the sludge from a sewage treatment plant in a city in western China and tailings from Dexing copper mine as the main raw materials to prepare ceramic granules, achieving the resource utilization of sludge. Xu [8] used urban sludge combined with clay, fly ash, and additives to prepare sludge bricks by calcination. The physical and mechanical properties of the sludge bricks were tested, providing ideas for the resource treatment and disposal of urban sludge. Xu [9] summarized the current research status of improving sandy soil with urban sludge. By analyzing the effects of using urban sludge for sandy soil restoration on planted vegetation and the potential risks to the ecological environment, the paper provided prospects for future research on improving sandy soil with urban sludge, aiming to promote the application of urban sludge composting in infertile soils such as sandy soil.

Currently, many scholars have conducted research on urban sludge treatment processes, but there are common issues such as low sludge utilization rate and high treatment costs. Especially for some new types of sludge treatment processes, although they have environmental advantages and generate less pollution, the high costs associated with these new processes hinder their widespread application due to the immaturity of the technology. Therefore, when selecting a urban sludge treatment process, both environmental and cost factors need to be considered. Based on existing research, this article proposes three widely applied urban sludge treatment routes: Route 1: drying and incineration treatment process; Route 2: pyrolysis process; Route 3: sludge composting process. Through a comprehensive comparative analysis of the technical characteristics and return on investment (ROI) of these three routes, the most economically feasible, technically mature, operationally practical, and environmentally friendly sludge treatment route is determined.

II. Research Method

This article adopts a comparative analysis research method, which involves comparing the data or characteristics of two or more entities, analyzing their differences, and revealing the development and changes of these entities to identify the optimal option. The focus of this article is to compare the technical characteristics and economic viability of three routes. By reviewing the literature, the technical characteristics of the three routes are compared, including their level of application maturity, operational complexity, and pollution levels. The economic viability of the three routes is compared through the calculation of the return on investment (ROI). The ROI is an economic evaluation indicator for technical projects, and a smaller value indicates better economic feasibility. After a comprehensive comparison of these two evaluation indicators, the best urban sludge treatment route is determined.

III. Results and Discussion

A. *Economic Analysis of Integrated Sludge Drying and Incineration Treatment Technology*

1) *Introduction to integrated sludge drying and incineration treatment technology*

The sludge drying and incineration treatment process consists of two main components: sludge drying and incineration, as shown in Fig. 1. Specifically, it includes the following main technologies: sludge storage and conveying system, drying system, incineration system, and waste heat recovery system. In addition to these, it also involves a series of auxiliary sludge treatment technologies, such as water supply system and odor removal system. The sludge drying and incineration process not only reduces the volume of sludge, but also effectively kills harmful microorganisms [10].

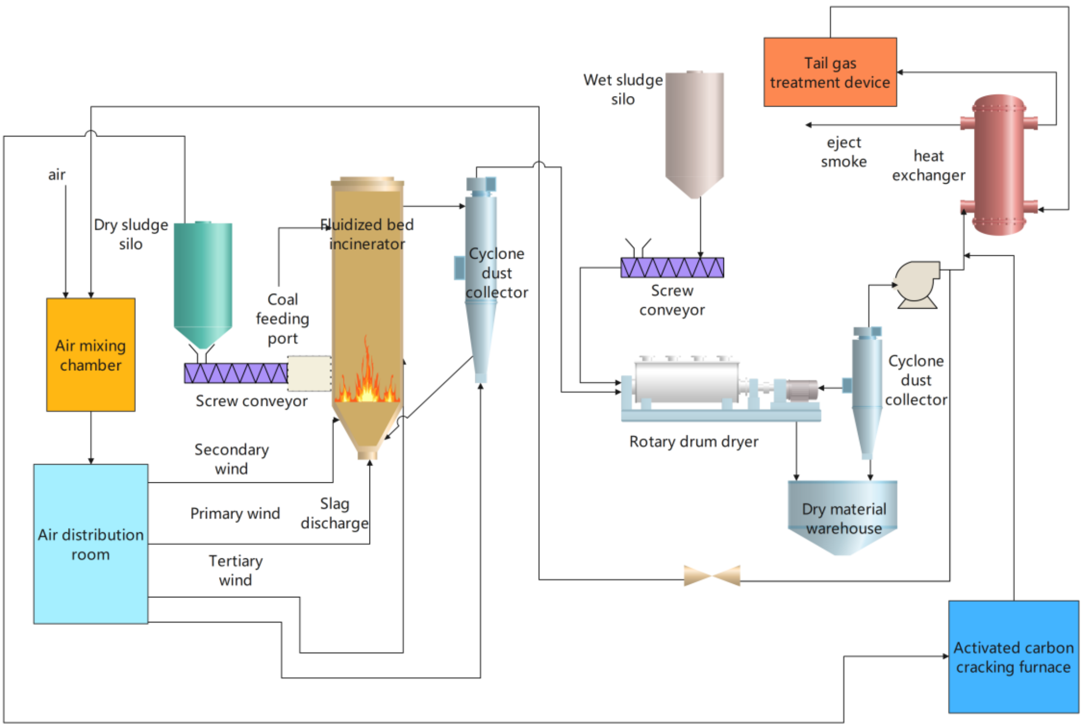

Fig. 1. Integrated sludge drying and incineration process flowchart.

2) *Technical analysis of co-firing sludge incineration system with coal*

Due to the comprehensive combustion mode of co-firing, the ignition performance of coal powder is significantly improved with the addition of sludge. Synergistic effects can be achieved in co-combustion under low temperature conditions. In recent years, as the country has been addressing global climate change and transitioning coal-fired power generation towards low-carbon energy, relevant notices and policies have been proposed. Therefore, co-firing of sludge in large-scale coal-fired power plants has become a practical method for sludge treatment and disposal, and has been widely applied in many regions [11], as shown in Fig. 2: Co-firing of Coal and Sewage Sludge Incineration Process Route.

The "dry + co-firing" process can increase the sludge treatment capacity while maintaining the thermal stability of combustion. Under proper mixing ratios, the emission requirements for conventional pollutants, heavy metals, dioxins, and other pollutants can be met [12]. In the "Notice on Carrying out Pilot Projects for Coal-biomass Cogeneration and Waste and Sludge Power Generation Technology Transformation" issued by the National Energy Administration in 2017, it was proposed to "prioritize cogeneration coal-fired units and layout coal-biomass cogeneration and waste and sludge power generation technology transformation projects", and 29 sludge co-firing power generation demonstration projects were approved in

2018 [13]. In China, there have been some new developments in coal-biomass cogeneration technology for sludge incineration. Through on-site co-firing experiments and numerical simulations, it has been found that there is no significant difference in NOx emissions and combustion performance compared to single coal powder incineration when the sludge co-firing rate is below 20%.

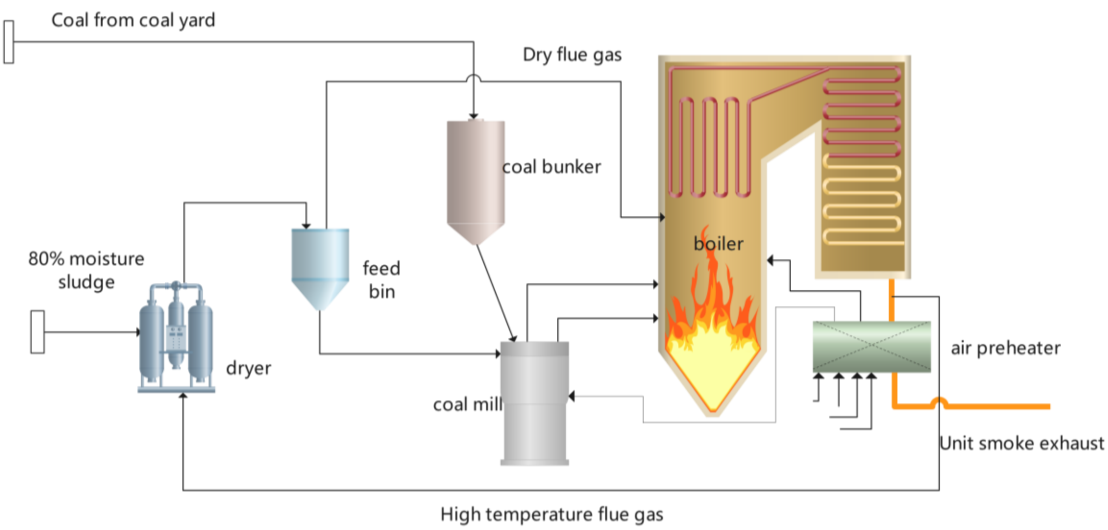

Fig. 2. Co-firing of coal and sewage sludge incineration process route.

3) Simulating the thermoeconomic performance of a coal-integrated sewage sludge incineration system using Ebsilon software

The current status of sewage sludge disposal in a 2×330 MW coal-fired cogeneration power plant is to fully utilize the equipment and technical advantages of the 2×330 MW coal-fired cogeneration units, and implement the construction of a coal-integrated sewage sludge power generation technology project. The scale of the project is designed to dispose of 350t of sewage sludge per day, with an annual disposal capacity of 128,000t [14]. The dried sludge is used as one of the raw materials along with coal powder to be co-fired in the boiler. In this study, Ebsilon software is used to simulate the power generation output at 100% THA condition with an assumed sludge mass co-firing ratio of 5%. Fig. 3 shows the power plant operation diagram of coal-integrated sewage sludge incineration simulated using Ebsilon software under 100% THA condition.

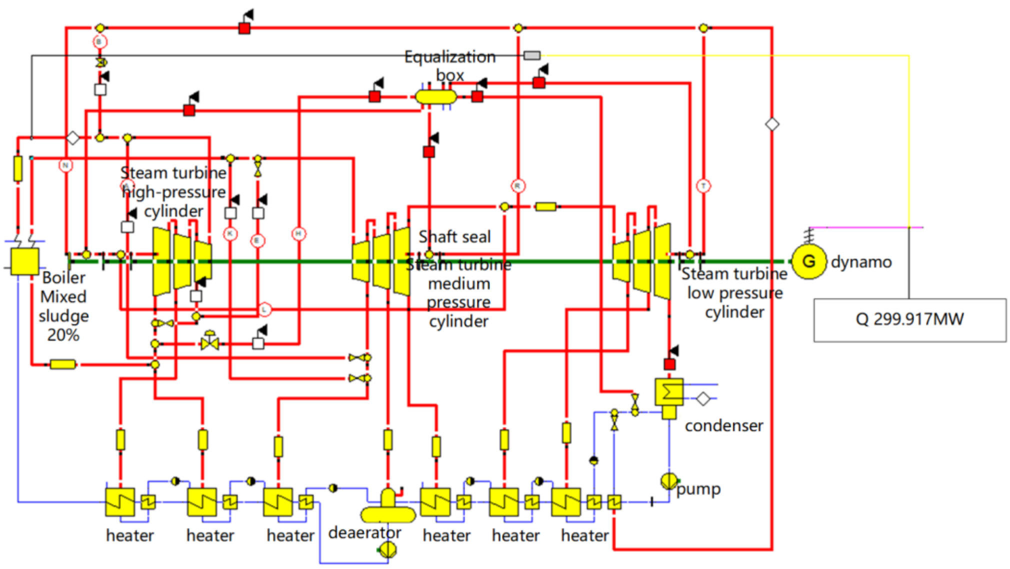

Fig. 3. The operational diagram of a coal-integrated sewage sludge incineration power plant simulated using Ebsilon software under 100% THA condition.

Table 1. Parameters such as electricity generation and coal consumption for a 300MW power plant unit

parameter	set
Power generation/MWh	1594454.91
Standard coal quantity for power generation /t	492709.26

According to Fig. 3, it can be observed that the power generation capacity of the unit under 100% THA condition is 299.917 MW. By referring to literature, the current market price of standard coal is 570 yuan per ton [15]. Typically, the profit from generating one kWh of electricity is 0.13 yuan for power plants. The return on investment (ROI) is the ratio of total investment to total revenue, which can be calculated based on Tables 1 and 2, and the total revenue of the 300 MW ultra-low emission investment is estimated to be around 324.243 million yuan, with a total investment of around 84 million yuan [16]. Based on the above data, the ROI of the coal-fired coupled sludge incineration system is 0.259.

Table 2. Operating costs of pollutant treatment processes

Technology	Running cost / Ten thousand yuan
desulphurization	2150
Denitration	1720
dust elimination	3670

B. Economic Analysis of Urban Sludge Pyrolysis Technology

1) Introduction to sludge pyrolysis technology

Sludge pyrolysis process is a method of heating sludge under atmospheric pressure or below the theoretical oxygen content, causing it to undergo dry distillation and thermal decomposition at a certain temperature, resulting in the conversion of sludge into hydrocarbons, and eventually obtaining four types of pyrolysis oil, condensate water, non-condensable gas, and char [17]. The pyrolysis process flowchart is shown in Fig. 4.

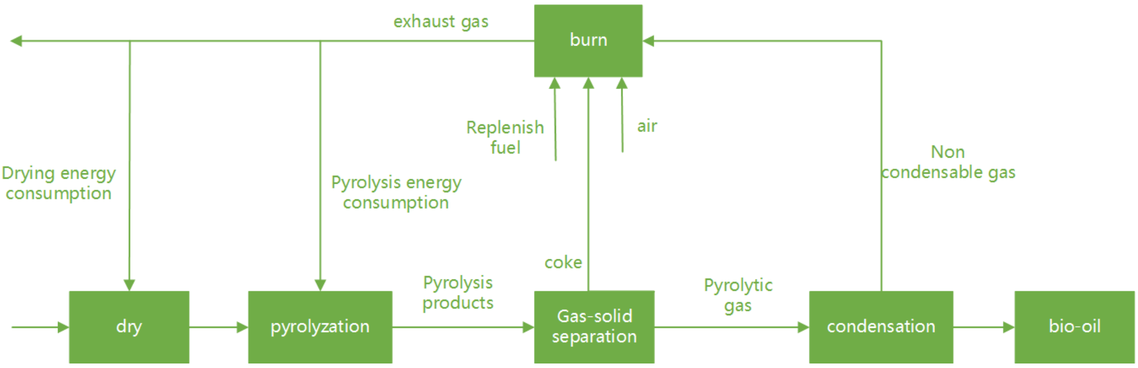

Fig. 4. Sludge pyrolysis process flowchart.

2) Analysis of sludge pyrolysis technology

Pyrolysis is a thermal decomposition process of organic matter under anaerobic conditions at medium to high temperatures (300–700 ℃). This process can yield bio-oil, biochar, and non-condensable gas. According to the heating rate and residence time, it can be divided into three categories: slow pyrolysis, which is carried out at lower heating rates and longer residence times to maximize biochar production; fast pyrolysis and flash pyrolysis, which are conducted at higher heating rates and shorter residence times to maximize bio-oil production.

Some researchers have utilized thermogravimetric analysis (TGA) to pyrolyze sewage sludge, and the results indicate that: a. the initial slight decomposition reaction occurs at temperatures ranging from 200 ℃ to 300 ℃, which corresponds to the decomposition of organic matter and dead biomass; b. the main decomposition occurs between 300 ℃ and 450 ℃, which is related to the natural macromolecules from the primary sludge; c. a smaller decomposition occurs at temperatures of 450 ℃ or higher, which may be associated with the thermal degradation of less biodegradable components such as cellulose material [18].

However, as the heating rate increases to a certain extent, the differences between various decomposition stages will diminish, and various organic compounds in wastewater will be decomposed at the same time. In a chemically inert environment, the unstable components of the initial volatiles will undergo secondary pyrolysis at around 600 ℃, resulting in the formation of hydrocarbons, non-hydrocarbons, and more stable aromatic compounds, including: a. water, b. hydrocarbons, c. oxygen-containing hydrocarbons, and d. nitrogen-containing compounds. The results indicate that temperature, residence time, pressure, sludge composition, sludge particle size, presence of catalysts, etc., are important factors that affect the yield of pyrolysis products from sludge and their characteristics [19].

3) Economic analysis of sludge pyrolysis

The profitability of pyrolysis equipment is closely related to the selling price of its products and the total cost. In this study, sludge from a wastewater treatment plant in Hubei Province was selected as the sample, with a pyrolysis temperature set at 500 ℃, a moisture content of around 80%, and a processing capacity of 5 t/h.

Table 3. The main design parameters of a sludge pyrolysis system

Item	Parameter
dry	3 MW
Drying system heat exchanger	3 MW
Pyrolysis furnace	4 MW
Pyrolysis system heat exchanger	1 MW
Combustion furnace	4 MW
Design life	25 year
Depreciation period of fixed assets	15 year
Discount rate	10%
Annual operating hours	6,000
Depreciation residual value rate	5%
Processing scale	5 t/h

The investment composition of the sludge pyrolysis for oil production plant at 500 ℃ is shown in Fig. 5. The wet sludge processing scale is 5 t/h, with an annual operation of 6,000 hours, requiring a total investment of approximately 21 million RMB. Among the total investment, 78% of the funds are used to purchase equipment, as sludge drying equipment accounts for a significant proportion in terms of capital and energy consumption in sludge thermal conversion processing technology. In the design of the pyrolysis unit, it is advisable to keep the transportation distance within 9 km.

Table 4. Economic indicators of sludge pyrolysis for oil production

Indicators	Value
Supplementary fuel cost (10000 yuan/year)	62
Operating cost (10000 yuan/year)	216
Total investment cost (10000 yuan)	1840
Annual income (10000 yuan)	415
Annual subsidy (10000 yuan)	270
Investment payback period (years)	15

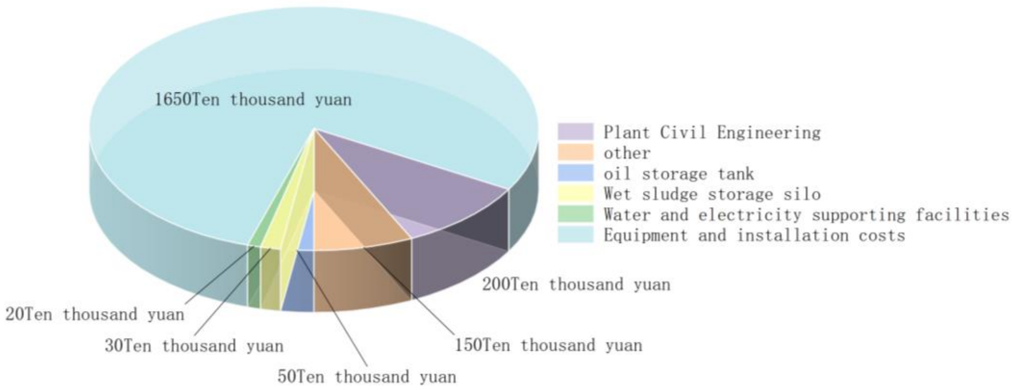

Fig. 5. Composition of investment in sludge pyrolysis for oil production plant.

The Return on Investment (ROI) is calculated as the ratio of total investment to total revenue. Based on the Tables 3 and 4, the total revenue of the sludge pyrolysis plant over 15 years of operation is estimated to be 102.75 million RMB, with a total investment of 62.70 million RMB. Therefore, the ROI for the sludge pyrolysis plant is calculated to be 0.61 [20].

C. Economic Analysis of Urban Sludge Composting Technology

1) Introduction to sludge composting process

Composting is essentially a high-temperature aerobic fermentation of sludge, using microorganisms in the sludge to carry out the fermentation process. Mixed with sludge, a certain proportion of bulking agents and conditioning agents, under moist conditions, the organic matter in the sludge is oxidized and degraded by microbial communities, resulting in the formation of humus-like substances. As humus-like substances can provide nutrients needed for plants, composting is a method of recycling and reusing sludge [21]. The process flow of aerobic composting is shown in Fig. 6.

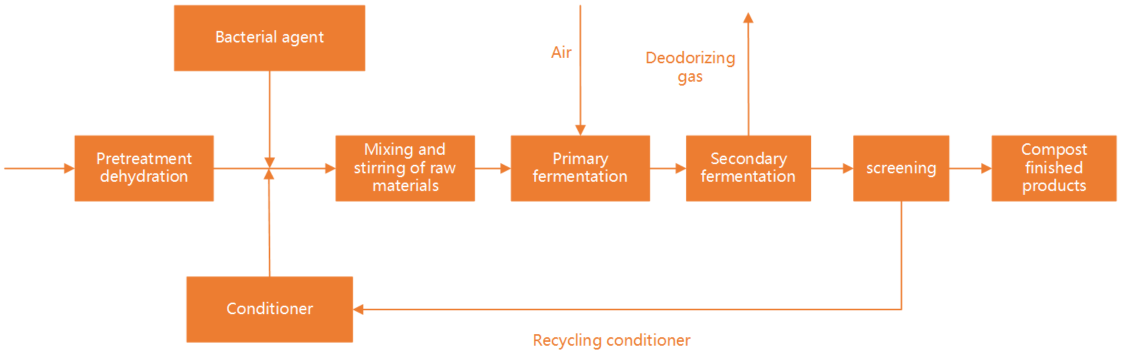

Fig. 6. Flowchart of aerobic composting process.

2) Analysis of composting technology

Aerobic composting is generally divided into three stages: 1) Initial stage, where readily decomposable organic materials are first broken down, generating heat and gradually increasing the temperature of the compost pile. 2) High-temperature phase, where the temperature rises above 45 °C, indicating the compost pile has entered the high-temperature phase, and mesophilic bacteria begin to die off as the temperature increases, with more than 90% of the bacteria losing their activity. 3) Cooling phase, where many degradable organic materials are depleted, and the temperature of the compost pile decreases. During this period, humus formation increases, resulting in humic acids and other stable organic compounds based on small molecule substances [22].

Aerobic composting of sludge utilizes the action of various microorganisms, including bacteria, actinomycetes, fungi, and protozoa, to degrade organic matter. Therefore, strict control of important process parameters is necessary to ensure the activity of microorganisms.

- Oxygen content: Adequate oxygen concentration is necessary for aerobic composting of sludge. In an aerobic environment, aerobic microorganisms can effectively degrade organic matter in the sludge, release energy, and increase the temperature of the compost pile [23].
- Temperature: Temperature is a critical factor in aerobic composting of sludge. Energy is generated when organic matter is decomposed by microorganisms, resulting in an increase in compost pile temperature and an acceleration of organic matter degradation in the sludge [24].
- C/N ratio: Carbon (C) and nitrogen (N) are major components of microorganisms, and they have a certain ratio in metabolism. A C/N ratio of 25-35 is generally considered suitable for the normal life of microorganisms.
- Moisture content: Microbial growth and metabolism are closely related to water, which is an important reaction medium. Microorganisms can only survive and degrade organic matter under moist conditions. However, if the moisture content of the compost pile is too high, the structure of the pile may become too compact, resulting in a low porosity and partial anaerobic reactions inside the pile [25].

- Amendment: Amendments are crucial in sludge composting. The characteristics of urban sludge, such as C/N ratio, moisture content, and structure, may not meet the requirements of aerobic composting. Therefore, adding appropriate amendments in aerobic composting can improve the C/N ratio of the materials, reduce moisture content, and ensure the normal operation of aerobic composting [26].

3) Economic analysis of composting

This chapter takes a wastewater treatment plant in Inner Mongolia as an example. The designed capacity of the composting plant for dewatered sludge is 150 t/day with a moisture content of 60%. This means that the plant can process 54,000 t of dewatered sludge per year.

The one-time investment for the infrastructure is 15.128 million yuan, and the initial fresh weight of the input materials is 63,500 t. If calculated on a 10-year period, the unit processing scale infrastructure investment is 238,000 yuan, and the total static investment for the first phase of composting is 63.285 million yuan.

Table 5. Various costs of composting process (unit: RMB 10,000)

Cost item	Value
Cost of structures and equipment	1513
Energy consumption cost of compost production	59.27
Depreciation cost of composting facilities	242.51
Other costs of composting	243.41
Cost of composting technology	632.85
production costs	342.08

Furthermore, since the total revenue of the first phase of composting is 185 million yuan and According to the Table V data, the Return on Investment (ROI) is calculated as the ratio of total investment to total revenue. Therefore, the ROI of the composting process studied in this chapter is 0.342 [27].

D. Economic Comparison

In this study, the calculated Return on Investment (ROI) for the coal-coupled sludge incineration system is 0.259, the ROI for the pyrolysis system is 0.61, and the ROI for the composting system is 0.342. ROI is an economic evaluation indicator for technological projects, and a smaller value indicates better economic viability. Therefore, based on the economic comparison, the coal-coupled sludge incineration system has the smallest ROI and the best economic viability.

E. Technical Analysis

- The pyrolysis technology for sludge requires strict conditions of medium to high temperature and anaerobic environment. If these conditions cannot be met, the yield of sludge pyrolysis will be greatly reduced.
- The composting process for sludge requires high environmental conditions such as low temperature, microbial activity, and moisture content. When the conditions are not suitable for microbial survival, the degradation efficiency of sludge will be reduced, resulting in a decrease in humus-like substances content and severely affecting the composting effectiveness.
- The coal-coupled sludge incineration process only requires stable combustion to efficiently treat sludge. This technology not only increases the proportion of non-fossil fuels, achieving energy saving and emission reduction goals, but also utilizes an efficient incinerator and flue gas treatment equipment to achieve efficient combustion and harmless treatment. Therefore, the coal-coupled sludge incineration process is superior to the other two processes in terms of technical aspects.

IV. Conclusion

This article employs a comparative analysis research method and concludes that the co-combustion of coal and sludge has the lowest return on investment (ROI), demonstrating the best economic performance. Additionally, this process is simpler to operate and exhibits higher stability. Moreover, the co-combustion process can be practically applied and promoted in large-scale coal-fired power plants. When sludge is co-fired, the boiler's thermal efficiency remains relatively unchanged. Under the condition of a 20% sludge co-firing ratio, the emissions of mercury, copper, manganese, nickel, and their compounds, dioxins, particulate matter, and other pollutants from the flue gas at the stack outlet all meet the emission requirements. The sludge treatment achieves true "resource utilization, energy recovery, harmlessness, reduction, and stabilization." Therefore, it can be concluded that the comprehensive treatment route of concentration + dewatering + drying + incineration is currently the most mature, widely applied, and suitable route for the development of urban sludge treatment in China. Sludge incineration technology will remain a pillar of sludge treatment and disposal in China for the foreseeable future.

Certainly, further improvements are needed for the co-combustion of coal and sludge technology to better align with environmental goals. This may include enhancing the co-firing of high-content sludge to minimize pollutant emissions during the solid waste combustion process. There is still much work to be done on reducing the release of pollutants. Moreover, it should be noted that the sludge case selected in this article is relatively limited, focusing on the study of sludge from a single wastewater treatment plant. In reality, there are significant variations in the elemental composition of sludge due to regional differences. Therefore, it is more scientifically rigorous to study multiple types of sludge. Furthermore, it is necessary to continue exploring more domestic and international sludge treatment solutions and investigate the impact of different sludge treatment devices, sludge conditions, and other factors on the final treatment results.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Fangxu Gui and Lai Wei conducted the study, Fangxu Gui, Peiyuan Pan, Heng Chen, and King Zhang analyzed the data, and Fangxu Gui wrote the paper; all authors had approved the final version.

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