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# Comparison of economic benefits for the utilization of reclaimed resources from wastewater treatment plants: a case study in Beijing

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## ABSTRACT

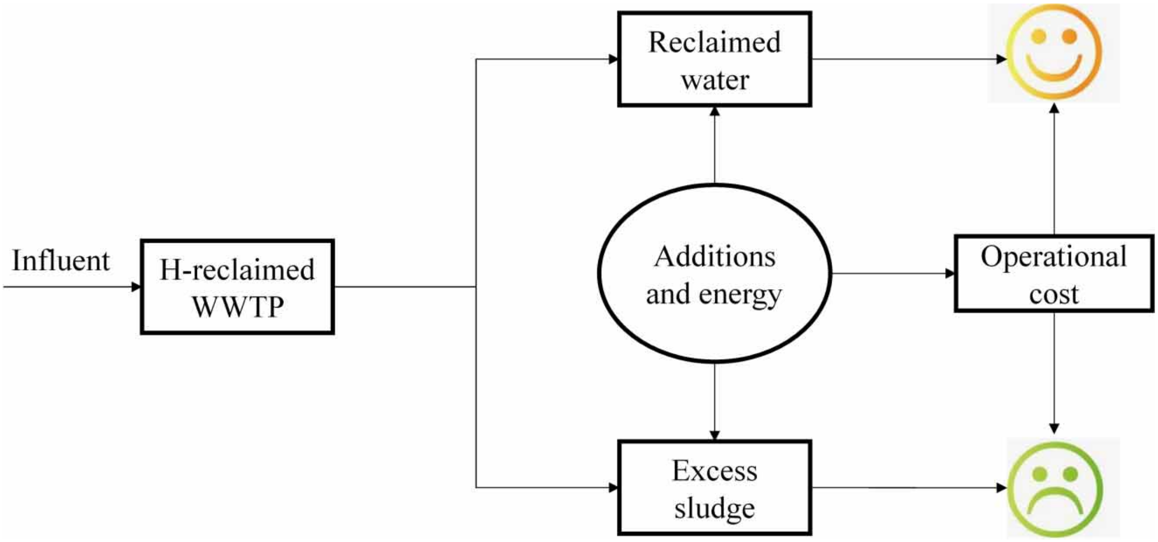
The fate of resource recovery is significantly influenced by the standards of water quality and bio-dried excess sludge for various applications. These standards must be practically attainable while ensuring public and environmental health, safety, and economic advantages. The present study investigates a reclaimed wastewater treatment plant (WWTP) in Beijing that incorporates both reclaimed water utilization facility and bio-dried excess sludge treatment. The study elucidates the standards for reclaimed water quality and bio-dried excess sludge for diverse applications. Notably, reclaimed water demonstrates substantial market demand in terms of economic benefits. However, bio-dried excess faces challenges due to higher operational costs and lower TP content. The heat power of the WWTP effluent water source can not only be harnessed for the bio-drying process blowers but also be elevated air temperatures to expedite the bio-drying process.

**Key words:** bio-dried excess sludge, economic benefits, reclaimed water, resource recovery, standards, wastewater treatment

## HIGHLIGHTS

- The H-reclaimed wastewater treatment plant successfully adheres to the limits of reclaimed water quality and bio-dried excess sludge.
- In contrast with the excess sludge, reclaimed water enjoys market demand, owing to its reduced operational cost.
- Using the heat power of the effluent water source could accelerate the bio-drying process of excess sludge.

## GRAPHICAL ABSTRACT



## 1. INTRODUCTION

Water is a crucial strategic resource within contemporary society, profoundly influencing the sustainable development of regional economies (Zhong *et al.* 2022). Water shortages are becoming one of the most typical ecological issues faced by all of humanity due to increasing global warming (Zhong *et al.* 2022). Unconventional water resources need to be increasingly implemented to ensure sufficient water supplies globally, satisfying the growing demand for water. Reclaimed water is one such reclaimed water (Mendoza-Espinosa *et al.* 2019), particularly applicable in urban areas. Water can be repurposed for various uses, necessitating the establishment of quantitative standards to determine its suitability for each distinct application (Mendoza-Espinosa *et al.* 2019). In light of this backdrop, wastewater treatment plants (WWTPs) have been established in greater numbers due to more stringent effluent standards. The Beijing Municipal Statistical Yearbook of Water Affairs reported that in 2020, the utilization of reclaimed water reached 0.12 billion tons, which was equivalent to 29.5% of the total water consumption. Given that water is a public resource, its reuse forms an integral part of a comprehensive approach to enhanced safety management. However, the operational costs associated with reclaimed water in China remain largely unexplored.

Excess sludge treatment and disposal is an important aspect of WWTP operation and has to be considered for the optimization of municipal wastewater management (Lu *et al.* 2019). Presently, Chinese WWTPs generate over 6 million tons of sludge on a dry matter basis, which is equivalent to more than 30,000 million tons of sludge containing 80% moisture content (Zhang *et al.* 2016). Consequently, the sludge outlet has become one of the major bottlenecks restricting the healthy development of wastewater treatment (Yang *et al.* 2015). Due to phosphorous (P) being a nutritional element necessary for the survival of all life forms, P recovery during nutrient removal from WWTPs has recently garnered much attention. Such recovery would be advantageous in terms of minimizing eutrophication and alleviating the scaling of process equipment (Hao *et al.* 2008). However, sanitary landfilling, incineration, and use as building materials are the dominant methods of safe sludge disposal in China, while the remaining portion (about 40%) is used for land application or illegally dumped (Zhang *et al.* 2016; MOHURD 2018). While the proportion of inappropriately disposed sludge has declined over time, significant quantities of pollutants still pose secondary environmental and ecological risks. The prevailing distribution of sludge management includes landfilling (50%), incineration (10%), materials recycling (9%), and composting (16%), with resource recycling (recycled building materials and compost) constituting only 25%, while untreated sludge accounts for 15% (Zhang *et al.* 2016). Additionally, in a recent study, Xie *et al.* (2023) conducted an assessment of the environmental sustainability and socio-economic costs of phosphorus recovery in China, employing life cycle assessment and costing methods. They found that recovering struvite as a phosphorus fertilizer exhibited the highest societal viability. Guo *et al.* (2010) compared the operational cost across the thermal drying aerobic, composting, and bio-drying methods in a previous study, revealing that thermal drying aerobic incurred the highest cost (230–280 yuan/t), followed by the aerobic reactors (80–100 yuan/t), and bio-drying with the lowest cost (60–80 yuan/t) (Guo *et al.* 2010). Despite the substantial gap that exists in comparison to the present, bio-drying remains the primary focus. Thermal energy recovery from WWTPs is another scarcely employed approach in China. Energy recovery can significantly contribute to benefit the total environment (as reported 71%). This aspect of thermal energy, however, does not receive adequate attention, even though thermal energy recovery plays a notable role (contributing around 40%) in enhancing the economic performance of WWTPs (Hao *et al.* 2019a, 2019b). Moreover, water source heat pumps (WSHPs) can harness and recover thermal energy (with 4 °C temperature differential) for heating, as indicated by a net energy production of 1.77 $kW \cdot h/m^3$ in Hao *et al.*'s study (Hao *et al.* 2019a, 2019b). If this energy can be applied to bio-process, substantial reductions in associated costs can be achieved. In summary, the integrated economic performance of WWTPs was influenced by factors such as reclaimed water, thermal energy recovery, and resource reclaimed (Hao *et al.* 2019a, 2019b).

In this study, reclaimed water (referred to as H-reclaimed) has been utilized for purposes, including supplementing rivers and lakes, industrial cooling, and non-contact domestic use by residents. The bio-dried excess sludge has potential applications as a fertilizer for scrub and woodland. The paper illustrates various standards for water quality and bio-dried excess sludge for distinct purposes. A comparison of economic benefits indicates that the disparity in utilization between the reclaimed water and bio-dried excess sludge in the WWTP could lead to varying market requirements.

## 2. RESOURCE RECOVERY GUIDELINE IN CHINA

### 2.1. Reclaimed water guidelines

Given the scarcity of water resources, numerous WWTPs have undertaken considerations for multifaced application, necessitating the establishment of quantitative criteria to assess water suitability for differing purposes (Mendoza-Espinosa *et al.* 2019). Many nations categorize the application of reclaimed water into planned or unplanned reuse industrial, municipal, and similar classifications (Mendoza-Espinosa *et al.* 2019). As a result, the water quality parameters must align with downstream uses, addressing concerns like risk assessment, mitigated risk, and monitoring frequency. In China, water is a communal resource overseen by the Ministry of Water Resources of the People's Republic of China by water laws. In the case of Beijing, reclaimed water accounted for 29.5% of the total water consumption, reaching 12 million $m^3$ annually in 2020 (Beijing Water Authority 2020).

### 2.2. Guidelines for the utilization of bio-dried excess sludge products

As treated wastewater quantities increase, the surplus excess sludge from WWTPs has notably surged, reaching 35.4 million tons (80% moisture content) by 2018 (MOHURD 2018). Methods such as landfilling, incineration, and using sludge as construction material pose secondary environmental and ecological risks. Given the importance of phosphate recovery for scrub and woodland fertilization, bio-dried cyclic products must adhere to the Pollutants Control Standards for Sludge Class A or B in agriculture according to China's guidelines (GB 4284-2018) (Ministry of Housing and Urban-Rural Development of The People Republic of China 2018).

### 2.3. Test and analysis

Key monitored indices for effluent water in reclaimed water include chemical oxygen demand (COD), biological oxygen demand (BOD), total phosphorous (TP), total nitrogen (TN), ammonia nitrogen $NH_3$-N, and others. The Ministry of Environmental Protection of the People's Republic of China published the 'Water and Wastewater Monitoring and Analysis Method' in 2002, which guided the detailed implementation of testing procedures (Ministry of Environmental Protection China (4th edition) 2002). For post-bio-dried excess sludge, inductively coupled plasma (ICP) emission spectrometry (ICP, Optical Emission Spectrometer, Optima 8,300 m Perkin, Elmer, USA) was employed to quantity metal element concentrations. Chemical analytical tests were performed at the reclaimed wastewater plant laboratory and sent quarterly to a third-party laboratory.

## 3. CASE STUDY

### 3.1. Background of the resource recovery

The H-reclaimed WWTP, a municipal facility in Beijing, commenced operations in November 2013 (Liu *et al.* 2018), which was located in Tongzhou New Town, Beijing, spanning an area of about 2,000 ha. It served approximately 1.65 million people. The effluent water quality from the H-reclaimed WWTP initially adhered to the first-level limit B of the Beijing municipal local standard 'Discharge Standards of Water Pollutants from Municipal Sewage Treatment Plants in Beijing' (DB11/890–2018) (Beijing Water Authority 2018) for discharge into receiving waters. During the operational period of the reclaimed water system in 2018, approximately 20,000 $m^3$/d of reclaimed water was regularly pumped for various urban purposes, such as miscellaneous urban uses, landscape environment, and industrial cooling. Furthermore, the bio-dried excess sludge plant (BDESTP) commenced operation in January 2018 (Hu *et al.* 2022). Subsequently, instead of the previous incineration method, excess sludge from the H-reclaimed WWTP has been transported to the BDESTP for further disposal via trucks at the facility. However, only a small portion of post-bio-dried excess sludge has been utilized due to its limited effectiveness as an effective fertilizer for local woodlands. The majority of this sludge has been transported via trucks to Tianjin for a process known as saline land improvement. The lower volume requirement of chemical fertilizer for equivalent efficiency offers ease of use, potentially hindering the widespread adoption of bio-dried excess sludge. Consequently, this approach may lead to secondary environmental and ecological risks. Figure 1 presents an aerial view, providing a detailed structural insight into the H-reclaimed WWTP and associated facilities.

### 3.2. Facilities and constructures of the reclaimed water system

Figure 2 illustrates the typical facilities and structures comprising the reclaimed water utilization system. The key components of the reclaimed water infrastructure included the reclaimed water storage basin (1), pumps (2),

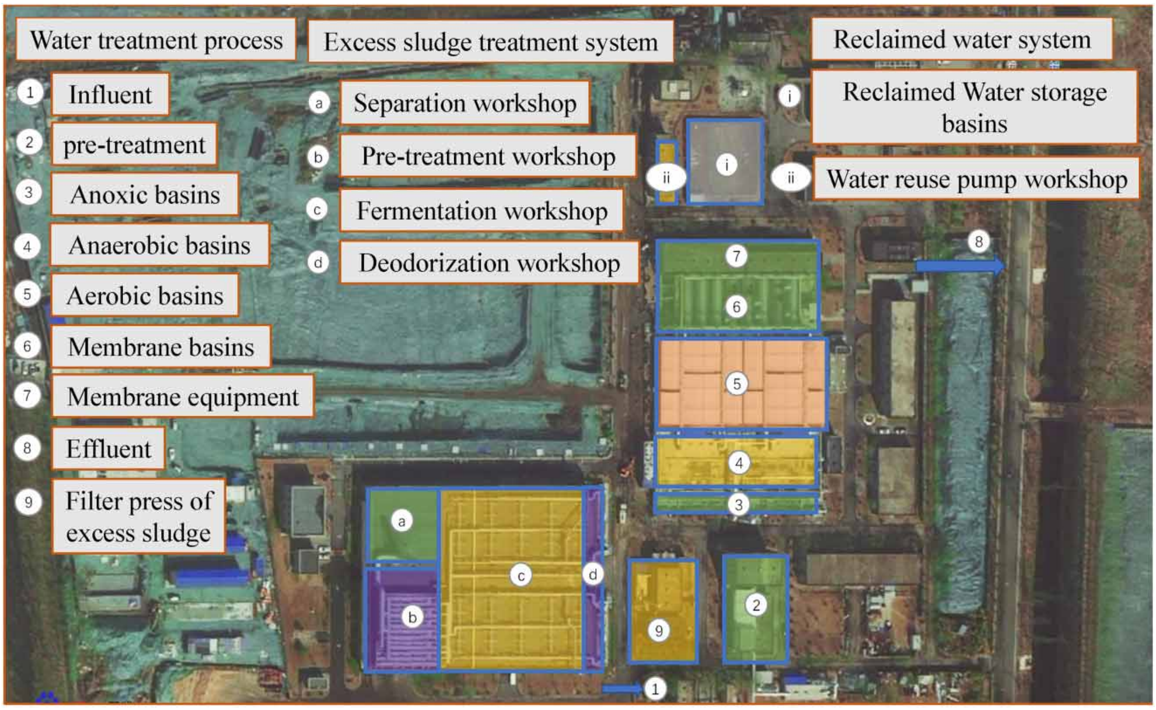


**Figure 1** | Aerial view of the H-reclaimed WWTP.

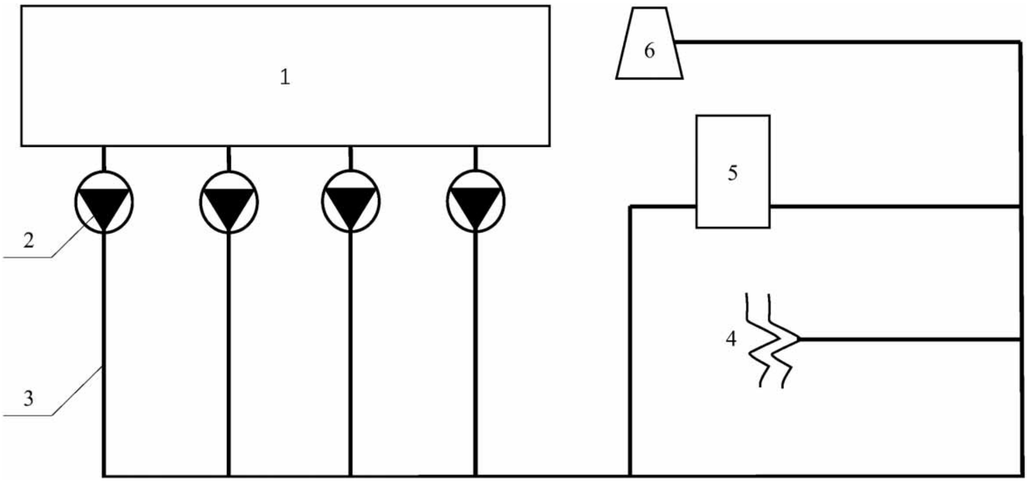


**Figure 2** | Schematic diagram of the reclaimed water reticulation infrastructure.

reclaimed water distribution network (3), and facilities for utilizing reclaimed water in landscape environments (4), urban miscellaneous uses (5), and industrial cooling (6).

Furthermore, the quantities of reclaimed water allocated used for urban miscellaneous purposes, landscape environments, and industrial cooling are approximately 3,000, 10,000, and 7,000 $m^3$/d, respectively.

### 3.3. Bio-dried excess sludge treatment process

The process for treating bio-dried excess sludge is outlined in Figure 3.

Effective excess sludge treatment and disposal constitute critical aspects of WWTP operations. The majority of Chinese WWTPs are equipped with facilities for sludge dewatering through pressure filtration, centrifugal dewatering, or plate pressure filtration (MOHURD 2018). Given the importance of phosphate as a finite limiting resource, phosphorus recovery is crucial to minimizing the environmental impact (Hao *et al.* 2019a, 2019b).

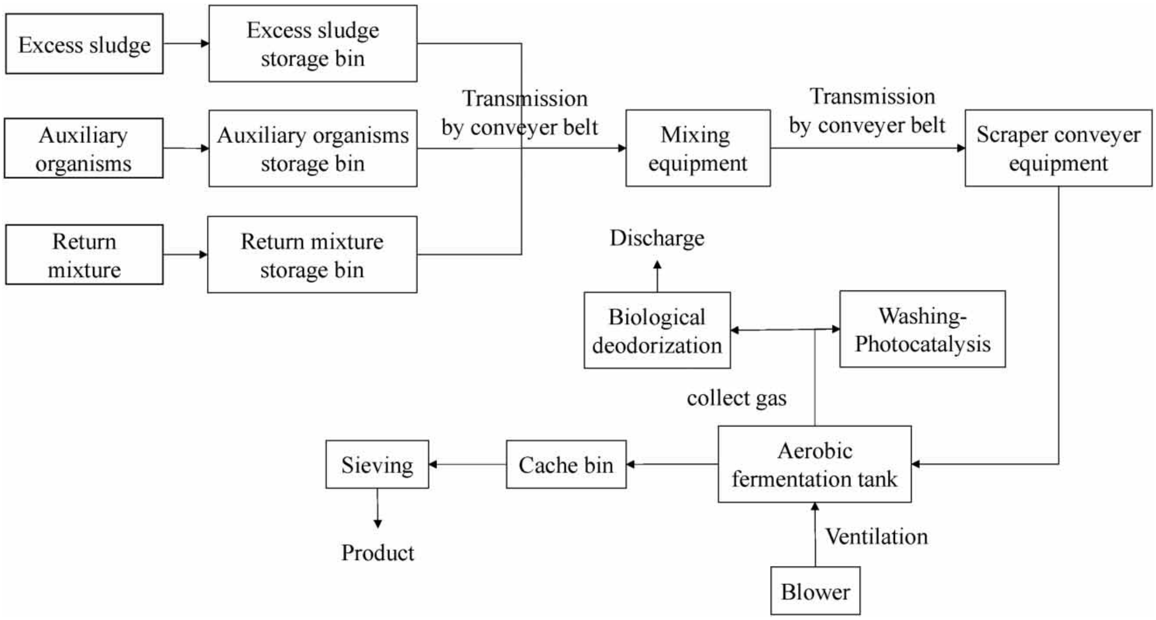


**Figure 3** | Flow chart of the bio-dried treatment process.

Wet sludge, auxiliary materials, and return mixtures are combined within the fermentation tank for bio-dried aerobic fermentation. The project utilizes a semi-static-closed tank aerobic fermentation process. The designed processing capability is 100 t/d, with an operational cycle of 20 days. The moisture content of the mixture is maintained between 55 and 65%, with a C/N ratio varying from 20:1 to 30:1 (Hu *et al.* 2022). The mixtures of porosity and C/N ratio provide favorable conditions for water removal and microbial fermentation. The wet sludge originates from the municipal sewage treatment plants in the project's vicinity. The moisture content of the wet sludge should not exceed 80% (Hu *et al.* 2022). Sizeable and rigid foreign materials should not be present in the wet sludge. The moisture content of the returned mixtures should be below 40%. The moisture content of auxiliary materials (mainly rice husk, mushroom residue, broken straw, etc.) should not exceed 12% in summer and 15% in winter. The pivotal parameter of the bio-dried process is the ratio of auxiliary materials, returned mixture, and wet sludge, which should be approximately 0.5:0.15:1 (Hu *et al.* 2022). Once the mixtures have dried following 20 days of fermentation, they are directed sent to the screening system. The return-mixture material contributes a wealth of microbial flora to the fermentation system. The primary monitoring indicators for excess sludge following the bio-dried treatment are presented in Table 1. These limits conform to the 'Standard for the Control of Pollutants in Agricultural Sludge' (GB 4284-2018) (Ministry of Housing and Urban-Rural Development of The People's Republic of China 2018).

**Table 1** | Major testing indexes of bio-dried excess sludge

| Constituent | Testing values |
|---|---|
| Total nitrogen (mg/kg) | $1.21 \times 10^4$ |
| Total phosphorus (mg/kg) | $2.03 \times 10^4$ |
| Total copper (mg/kg) | 72.8 |
| Total mercury (mg/kg) | 5.08 |
| Total chromium (mg/kg) | 51.3 |
| Total lead (mg/kg) | 15.1 |
| Total cadmium (mg/kg) | 1.46 |
| Total potassium (mg/kg) | $3.40 \times 10^3$ |
| pH | 7.18 |
| Fecal coliform (N/L) | >11.1 |

The total phosphorus content reaches 2.03% (Table 1), which is significantly lower than that of typical chemical fertilizers (>7%), as listed in Table 1. The limited TP content in the bio-dried excess sludge is the primary reason for its low demand. In comparison to post-bio-dried excess sludge, people might prefer using chemical fertilizer. The values provided above are derived from the design and monitoring reference from the consulting engineers and on-site operational staff experience (Hu *et al.* 2022).

### 3.4. Operating cost of reclaimed water

Table 2 presents a summary of the operating costs in a total year associated with reclaimed water, considering a utilization rate of 20,000 $m^3$/d. In China, operational costs are typically classified into the power costs of equipment, additional costs for P and N removal, and monitoring costs mandated by local government regulations. The calculated total operating cost for the bio-drying process was approximately 0.47 yuan/t.

**Table 2** | Daily operating cost of reclaimed water in a total year

| | Individual costs | Percent of costs (%) | Costs per ton |
|---|---|---|---|
| Power costs | ¥1,028,547 | 30.08 | ¥0.14 |
| Agent costs | ¥21,900,007 | 64.05 | ¥0.30 |
| Monitoring costs | ¥1,924,357 | 5.63 | ¥0.03 |
| Equipment calibration costs | ¥80,007 | 0.24 | ¥0.001 |
| Total cost | ¥3,418,982 | 100.00 | ¥0.47 |

However, the typical price of tap water during phase I in Beijing was 5.0 yuan/t (Beijing Municipal Commission of Development and Reform 2014), significantly surpassing the cost of reclaimed water. The substantial disparity between the price of tap water and the cost of reclaimed water favored the utilization of reclaimed water. A substantial subsidy might be required by business companies for reclaimed water from the local government. However, in the case of Beijing, this seemed unnecessary due to the adoption of a three-step cumulative markup for tap water prices.

### 3.5. Operating cost of bio-dried excess sludge

The operational cost of the process was calculated based on the operational data from November 2020. The total quantity treated in the month was 3,043 tons. The operating costs consisted of power cost, oil cost, auxiliary material cost, and monitoring cost, alongside labor cost. The calculated cost for sludge fermentation was approximately 309 yuan/t as detailed in Table 3 (Hu *et al.* 2022). Among these factors, auxiliary material costs constituted a dominant portion of the overall operational cost.

**Table 3** | Operating cost of the BDESTP

| | Individual cost | Percent of cost (%) | Costs per ton |
|---|---|---|---|
| Power cost | ¥272,739 | 29.1 | 90 |
| Fuel cost | ¥31,694 | 3.3 | 10 |
| Monitoring cost | ¥10,130 | 1.1 | 3 |
| Auxiliary material cost | ¥624,491 | 66.5 | 205 |
| Total cost | ¥939,045 | 100.0 | 309 |

In recent times, auxiliary materials prices have witnessed a significant increase, particularly since the project relies on materials transported from other regions due to air quality regulations in sensitive areas. The electricity cost for the deodorizer fan is notably higher than other bio-dried facilities due to the stringent air quality requirements. Consequently, electricity and auxiliary materials accounted for 29.1 and 66.5% of costs, respectively (Hu *et al.* 2022). The odor treatment fans, with a combined power of 120 kW, must operate continuously due to design-related system limitations that affect air quality. The aeration blowers, with a total power of 150 kW (20 × 7.5 kW), operate intermittently based on temperature moisture and the environment temperature (Hu *et al.* 2022). Notably, the BDESTP operates at full capacity, given that it is more cost-effective and environmentally friendly in contrast to incineration. Incineration costs for excess sludge were found to be around 500 yuan/t, gradually increasing over the years due to limited disposal options.

## 4. INTEGRATED RESCOURCE RECOVERY MANAGEMENT RECOMMENDATION

Considering the substantial potential for heat exchange, effluent energy from WWTPs emerges as a viable energy source. Municipal sewage has stable flow, sufficient water availability, and residual temperature. Notably, biological desiccation of surplus sludge necessitates significant energy input. In practice, prolonged cold air aeration in winter, such as Beijing, can result in frozen wet excess sludge. Hao *et al.* (2019a, 2019b) demonstrated that the WSHP could recover thermal energy (with a 4 °C temperature difference) for heating, generating 1.77 $\text{kW·h/m}^3$ of net energy production, an approach adopted in this study. Effluent energy from the WWTP amounts to 1,475 kW ($1.77 \times 20{,}000 \div 7.5 = 1{,}475$ kW), whereas the combined power consumption of all fans in the bio-dried treatment plant totals only 270 kW ($120 + 150 = 270$ kW). The energy from the effluent water source is sufficient to meet the power requirements of all the fans in the bio-dried sludge treatment plant, and the remaining energy is still utilized as electric power. In addition to heating the cold air, the residual energy is employed to desiccate the sludge and expedite the bio-drying process of excess sludge. This approach could potentially lower the effluent water temperatures, contributing to the inhibition of microorganism growth within the reclaimed water distribution network.

## 5. CONCLUSION AND POLICY RECOMMENDATIONS

Comparative analysis against the relevant standards reveals that both the primary monitored indicators of bio-dried excess sludge and reclaimed water meet regulatory guidelines. The operating cost for the reclaimed water treatment amounts to 0.47 yuan/t, whereas bio-dried excess sludge incurs costs of 309 yuan/t. Given its higher operational expenses and lower TP content, bio-dried excess sludge faces challenges in terms of market demand. The substantial price disparity between tap water and reclaimed water fosters the favorability of reclaimed water utilization. Effluent water energy serves not only to expedite the bio-drying of excess sludge but also to adequate power of all fans within the bio-dried excess sludge plant, as calculated.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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