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Research on Sludge Bio-Drying Process with Membrane Cover Technology: A Case Study of Engineering Practice in Guangze County

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Abstract: To achieve efficient reduction and resource utilization of municipal sludge, this study combines metabolic heat generation by thermophilic bacteria with e-PTFE membrane cover technology in a full-scale sludge bio-drying engineering practice with a treatment capacity of 100 t/d in Guangze County, Fujian Province. The results show that the optimal mixing ratio is sludge: rice husk: recycled material = 1:1:0.1 (volume ratio). Under this condition, the maximum pile temperature reaches 88.9 °C, and the temperature above 70 °C can be maintained for more than 10 days. At the end of the bio-drying period (15 days), the moisture content of the product decreases from an initial 56% to 25%–30%, the weight reduction rate reaches 50%–70%, and the bulk density decreases from 0.7 t/m³ to 0.45 t/m³. The product has an organic matter content of 56.66%, total nutrients of 5.84%, a seed germination index (GI) of 0.725, a maturity index (E4/E6) of 2.66, and heavy metal contents below the national standard limits. Metagenomic analysis reveals that during the hyperthermophilic phase, the family Streptosporangiaceae (relative abundance 43%) within the phylum Actinobacteria becomes the core functional microbiota driving macromolecular organic matter degradation and biological heat production. This process requires no external heat source for maintenance and achieves deep dewatering, stabilization, and harmlessness of sludge within 15 days.

Keywords: Sludge Dewatering; Thermophilic Bacteria; Bio-Drying; Membrane Cover

1. Introduction

By 2024, the urban sewage treatment rate in China has exceeded 98%, and the annual production of associated sludge (with a moisture content of approximately 80%) has surpassed 60 million tons [1,2]. Sludge is characterized by high moisture content and a tendency to putrefy. Traditional landfill disposal not only occupies large amounts of land but also easily causes secondary pollution from leachate; incineration faces challenges such as high energy consumption and significant carbon emissions [3,4]. Bio-drying technology utilizes metabolic heat from aerobic microorganisms to evaporate water, offering advantages of low energy consumption and reduced carbon emissions [5]. However, conventional processes generally suffer from long start-up periods and difficulty in maintaining high temperatures [2,6,7]. Thermophilic bacteria (with optimal growth temperatures of 60–90 °C) can efficiently degrade organic matter and release substantial biological heat under high-temperature conditions [8]. The membrane cover, which combines moisture permeability, waterproofing, thermal insulation, and odor control functions, creates a favorable hydrothermal microenvironment for the pile [9,10].

Our research team has preliminarily validated the feasibility of coupling thermophilic bacteria with membrane cover technology in previous small-scale and pilot studies. Based on this, this paper systematically investigates the temperature variation, dewatering and reduction effects, product resource quality, and microbial community driving mechanisms during the bio-drying process under the optimal mixing ratio (sludge:rice husk:recycled material = 1:1:0.1) in the 100 t/d project in Guangze County, aiming to provide engineering reference and theoretical support for low-carbon municipal sludge treatment.

2. Materials and Methods

2.1 Project Overview

The project is located in Guangze County, Nanping City, Fujian Province, with a designed daily treatment capacity of 100 tons of dewatered sludge (initial moisture content 80%). Three parallel bio-drying tanks were constructed, each with dimensions of 15 m (length) × 6.5 m (width) × 2.8 m (height), providing an effective volume of 273 m^3. The tank walls adopt a trapezoidal common-wall design to reduce civil construction costs.

2.2 Membrane Cover Material

The project uses the AT-DF800 e-PTFE nano-functional membrane cover, which has a three-layer composite structure: the middle layer is an e-PTFE functional membrane, and the upper and lower layers are polyester oxford fabric protective layers. The main performance parameters are as follows: moisture permeability ≥ 10000 g/(m^2·24h), hydrostatic pressure ≥ 20000 mmHg, air permeability ≥ 2 L/(m^3·s), radial breaking strength ≥ 5000 N, and odor barrier capacity complying with GB 14554-1993 standards (≤ level 2). This membrane is designed for 8–10 years of reuse under open-air conditions.

2.3 Mixing Ratio and Process Flow

The optimal mixing ratio is sludge:rice husk:recycled material = 1:1:0.1 (volume ratio). The sludge is dewatered sludge from the local municipal wastewater treatment plant (initial moisture content ~80%); rice husk (C/N ratio 62–72, moisture content 10%–15%) serves as a bulking agent; the recycled material is the bio-dried product from the previous batch, which also functions as an inoculum of thermophilic bacteria. After mixing, the initial moisture content is controlled at 55%–60%, the C/N ratio is adjusted to 20–30, and the initial bulk density is approximately 0.7 t/m^3.

The process flow is as follows: materials are mixed uniformly by a shovel loader and then fed into the bio-drying tank, with a pile height of 2.5 m. Aeration pipes are embedded at the bottom of the tank, and forced aeration is provided by variable-frequency fans. Auxiliary heating is supplied only for the first 12 hours to activate microbial activity; subsequent bio-drying relies entirely on microbial metabolic heat to maintain the temperature. The entire bio-drying period lasts 15 days, with one mechanical turning performed on days 7–8. The membrane cover remains over the pile throughout the process, eliminating the need for separate odor control facilities. As shown in Figure 1.

Figure 1. Sludge Bio-Drying with Membrane Cover

2.4 Analytical Methods

Temperature: Real-time monitoring using PT100 thermocouples with data recorded at 1-hour intervals.

Moisture content: Determined by oven drying at 105 °C.

Bulk density: Measured by the ring knife method.

Organic matter: Determined by the muffle furnace ignition method at 550 °C.

Total nutrients: Total nitrogen by Kjeldahl method, total phosphorus by vanadomolybdate yellow spectrophotometry, total potassium by flame photometry.

Seed germination index (GI): Soybean seeds were used as test material. Samples were extracted, and the germination index was calculated as GI = (germination rate of extract treatment × average root length) / (germination rate of control × average root length) × 100%.

Maturity index (E4/E6): Determined by UV spectrophotometry measuring absorbance at 465 nm and 665 nm and calculating the ratio.

Heavy metals: Determined by inductively coupled plasma mass spectrometry (ICP-MS).

Metagenomic analysis: Representative samples were collected at four stages: initial after mixing (D0), heating phase at 60 °C (D3), hyperthermophilic phase at 80 °C (D5), and end of bio-drying (D15). Samples were snap-frozen in liquid nitrogen and sent for metagenomic sequencing.

3. Results and Discussion

3.1 Temperature Variation during the Bio-Drying Process

The pile temperature variation exhibited a typical three-stage pattern: "heating – high temperature – stabilization." After 12 hours of auxiliary heating, the pile temperature rapidly increased from an initial 31 °C to 71.6 °C and reached a peak of 88.9 °C the following day. Subsequently, the pile temperature remained stable in the hyperthermophilic range of 70–88 °C for more than 10 days. During the mechanical turning on days 7–8, the temperature temporarily dropped to approximately 60 °C, but due to the high metabolic activity of the thermophilic bacterial community and good thermal insulation of the pile, it quickly recovered to above 80 °C within 24 hours. At the end of the bio-drying period (days 12–15), as the readily degradable organic matter was largely exhausted, the temperature gradually decreased to below 50 °C. As shown in Figure 2.

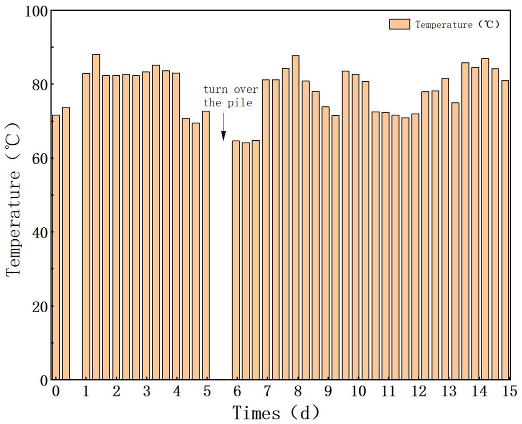

Figure 2. Temperature Variation during the Bio-Drying Process

This ability to maintain hyperthermophilic conditions (>80 °C) for an extended period can be attributed to two core mechanisms: First, the recycled material enriched with thermophilic microorganisms provides an efficient "inoculation effect," enabling rapid initiation of organic matter degradation and heat production; second, the high thermal resistance of the e-PTFE membrane cover significantly reduces heat loss from the pile to the environment, creating a "biological heat pump" effect [5,10].

Compared to conventional composting or bio-drying processes, which typically maintain temperatures only in the range of 55–65 °C, this process successfully elevates the high-temperature range to 70–88 °C, greatly enhancing the thermodynamic driving force for water evaporation.

3.2 Moisture Content Variation and Reduction Efficiency Analysis

Under optimal conditions, the initial moisture content of the material was approximately 56%. It decreased to 45% on day 3, 35% on day 7, below 30% on day 12, and finally stabilized at 25%–30% at the end of the process. The total moisture removal rate over the entire period exceeded 50%.

The material reduction effect was significant: taking a single tank as an example, the total feed weight (wet basis) before bio-drying was about 55–60 tons, which decreased to 16–18 tons after bio-drying, achieving a weight reduction rate of 50%–70%. The bulk density of the material decreased from an initial 0.7 t/m³ to an average of 0.45 t/m³, indicating substantial volume reduction as well.

Vertical stratification sampling (upper, middle, and lower layers) of the pile revealed that the moisture content of the upper layer was 30.26%, the middle layer 39.21%, and the bottom layer 45.09%, showing a clear "upper dry, lower wet" gradient. This phenomenon is due to the condensation and reflux of high-temperature saturated hot air rising from the middle of the pile upon contact with the relatively cooler membrane cover; the bottom material receives some of this condensate, and the higher resistance to bottom aeration reduces water evaporation efficiency. This result confirms the necessity of one mechanical turning in the middle of the process: mechanical disturbance brings the high-moisture bottom material to the middle and upper layers, re-establishing a uniform pore structure and effectively avoiding incomplete drying in localized areas.

3.3 Evaluation of Bio-Dried Product

The main physicochemical properties of the product under optimal conditions are shown in Table 1. The organic matter content reached 56.66%, total nutrients (N+P2O5+K2O) were 5.84% (total nitrogen 2.22%, total phosphorus 2.86%, total potassium 0.76%), pH was 7.38, and moisture content was 20.04%. Heavy metal contents were all below the standard limits, with arsenic at 6.4 mg/kg, far below the limit of 75 mg/kg specified in "Disposal of sludge from municipal wastewater treatment plant - Quality of sludge used in landscaping" (GB/T 23486-2009); cadmium, lead, chromium, and mercury were not detected or were below detection limits.

The seed germination index (GI) was 72.5%. Although the "Organic Fertilizer" standard (NY/T 525-2021) primarily targets traditional

organic fertilizers, its GI ≥ 70% maturity threshold can still be used as a reference – our product exceeds this value, indicating that phytotoxicity has been largely eliminated [8].
The maturity index E4/E6 was 2.66, much lower than the value of 5–8 for untreated sludge. This indicates that the humic acid molecules in the product have a high degree of aromatic ring condensation and high molecular weight, with properties close to those of mature compost or peat soil.

Table 1. Main Physicochemical Properties of the Bio-Dried Product

Parameter	Measured value	Standard limit (landscaping)
Organic matter (%)	56.66	≥25
Total nutrients (%)	5.84	≥3
Moisture content (%)	20.04	≤40
pH	7.38	6.0–8.5
Arsenic (mg/kg)	6.4	≤75

In summary, this bio-dried product can be safely applied in various land-use scenarios such as landscaping, poor soil improvement, and mine ecological restoration. As shown in Figure 3.

Figure 3. Final Bio-Dried Product

3.4 Microbial Community Succession

Metagenomic analysis results show that the average relative abundance of the bacterial domain is as high as 99.16%, while archaea account for only 0.72%, confirming the absolute dominance of bacteria in the bio-drying process. The microbial community succession exhibits significant stage-specific changes, with key nodes analyzed as follows:
Heating phase (D0–D3, 60 °C): The phylum Firmicutes dominated, with its various groups together accounting for over 57% relative abundance. This group typically contains many fermentative bacteria capable of rapidly decomposing simple carbohydrates and proteins under mesophilic conditions, and their active metabolism provides the main heat source for initial pile heating. Meanwhile, the phyla Bacteroidota and Proteobacteria served as important auxiliary groups, jointly participating in the initial degradation of organic matter. By the D3 stage, Firmicutes still maintained a dominant position, but their internal structure underwent significant reorganization – among them, the specific taxon Bacillus decreased markedly from 32.85% to 8.31%, indicating that a clear population turnover within Firmicutes had already occurred as the temperature increased.
Hyperthermophilic phase (D5, 80 °C): The relative abundance of Firmicutes dropped sharply from its dominant level at D3 to approximately 3%, a decrease of about 54 percentage points, showing that most non-thermotolerant groups were significantly inhibited or even died off under extreme high-temperature conditions. Actinobacteria underwent explosive growth, with its relative abundance soaring from about 2% at D3 to 58%. Bacteroidota decreased to 7.53%; some dominant members of this phylum are associated with the degradation of organic matter, complex polysaccharides, and cellulose under mesophilic conditions. When the temperature exceeds their tolerance threshold, their cell membranes, proteins, and nucleic acids are susceptible to thermal inactivation, leading to a significant decrease in relative abundance.
End of bio-drying (D15): As the pile entered the maturation phase, the community structure stabilized, exhibiting a pattern of two dominant phyla. Actinobacteria decreased from its peak value to 35.99%, while Proteobacteria further increased to 37.11%, with both jointly dominating the mature-stage community. Proteobacteria contains many groups involved in the nitrogen cycle, humus formation, and other processes, which are closely related to the mineralization of nitrogen-containing organic substrates, nutrient transformation, and humification. The increase in its abundance typically indicates that the pile has entered the maturation and nutrient stabilization phase.

4. Conclusions

(1) Using the mixing ratio sludge:rice husk:recycled material = 1:1:0.1, under the synergistic effect of membrane cover and thermophilic bacteria, the peak pile temperature can reach 88.9 °C, and the high temperature

above 70 °C can be stably maintained for more than 10 days, achieving efficient sterilization and rapid dewatering.

(2) Within the 15-day bio-drying period, the moisture content of the product decreased from 56% to 25%–30%, the weight reduction rate reached 50%–70%, and the bulk density decreased from 0.7 t/m³ to 0.45 t/m³, realizing deep dewatering and efficient volume reduction of sludge.

(3) The bio-dried product has an organic matter content of 56.66%, total nutrients of 5.84%, a seed germination index (GI) of 72.5%, a maturity index (E4/E6) of 2.66, and heavy metal contents meeting national standards, indicating good potential for resource utilization, meeting the requirements for landscaping and soil improvement.

(4) From the perspective of microbial mechanisms, the bacterial domain is the main driver of the bio-drying process. During the heating phase, Firmicutes (abundance >57%) rapidly initiate organic matter degradation and heat production; during the hyperthermophilic phase, Actinobacteria (abundance 58%) take over as the core heat-producing functional group; during the maturation phase, Proteobacteria (37.11%) and Actinobacteria (35.99%) jointly dominate nutrient transformation and humification. The shift in metabolic pathways from glycolysis to ketone body metabolism and osmotic pressure defense is a key adaptive mechanism that maintains system stability under extreme high temperatures.

(5) This process requires only 12 hours of auxiliary heating during the start-up phase, and during operation it needs no external heat source or independent odor control facilities, resulting in low operating costs. It is a low-carbon, efficient sludge treatment pathway with good potential for promotion.

References

[1] Zhu Weina, Shi Yongtao. Energy self-sufficiency of digestate drying by methane production from co-anaerobic digestion of municipal sludge and kitchen waste for heating. China Biogas, 2026, 44(02): 65-71.

[2] Chen L., et al. Mechanistic insights into the sludge biodrying process: the evolution of sludge structure and microbial community. Environmental Technology, 2025. DOI: 10.1080/09593330.2025.2564904.

[3] Dai Xiaohu. Current situation of municipal sludge treatment and disposal in China and analysis of "carbon neutrality" pathways. Water & Wastewater Engineering, 2021, 47(3): 1-5.

[4] Wang Lin, Li Debin, Liu Ziwei, et al. Carbon emission analysis of sludge treatment and disposal pathways. China Environmental Science, 2022, 42(5): 2404-2412.

[5] Chang H.M., Zhao Y., Xu A.K., et al. Mini-review of inventory data for the dewatering and drying of sewage sludge. Waste Management & Research, 2023, 41(6): 1081-1088.

[6] Wu K., Zhu R.C., Li P.Y., et al. Variations of organic matters and bacterial community during hyperthermophilic biodrying process of sewage sludge. Drying Technology, 2022, 40(14): 2920-2929.

[7] Xue Zhaojun, Zhou Guoya, Yu Xiaofeng, et al. Treatment of excess sludge by hyperthermophilic self-heating aerobic composting process. China Environmental Science, 2017, 37(9): 3399-3406.

[8] Yu Zhen, Zhou Shungui. Hyperthermophilic aerobic fermentation technology: mechanisms of rapid composting maturity and pollution control. Journal of Nanjing Agricultural University, 2020, 43(5): 781-789.

[9] Composting of sewage sludge with mole cricket: stability, maturity and sanitation aspects. International Journal of Environmental Science and Technology, 2019, 16: 5827-5834.

[10] Zou Jinlin, Li Weiguang, Wu Chuandong, et al. Study on the influence of two PTFE membranes on sludge aerobic fermentation parameters. Water & Wastewater Engineering, 2016, 52(4): 37-40.