

Article

Study on Drying of Municipal Sludge and Pollutants Release Characteristics

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Abstract: With the rapid development of China's economy, urban domestic sewage and industrial wastewater treatment efficiency has improved, resulting in a significant increase in sludge production. Thermal drying is essential for reducing, safely disposing of, and resourcefully utilizing sludge. However, this drying process inevitably releases harmful pollutants, posing potential environmental risks that necessitate careful management. This work focused on the thermal drying of municipal sludge at five temperature intervals (90–210 °C) and examined the impact of calcium oxide on sludge drying properties. The results indicated that higher temperatures increased sludge drying rates, with optimal efficiency achieved at a 15% calcium oxide addition. Online detection of NH₃, H₂S, CO, and CH₄ in the exhaust gas revealed that pollutant generation was temperature-dependent. While calcium oxide addition had no significant effect on CH₄ and CO emissions, it significantly inhibited the generation of H₂S and NH₃. This work provided crucial insights into optimizing sludge treatment, which improved drying efficiency and mitigated the release of hazardous pollutants, thereby reducing potential environmental and health risks associated with sludge disposal.

Keywords: municipal sludge treatment; thermal drying; control optimization; calcium oxide; pollutant emissions



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1. Introduction

The escalating global production of sludge is a multifaceted issue, stemming from rapid urbanization and the expansion of industrial activities. These factors contribute to an increasing volume of wastewater worldwide, consequently driving up the output of sludge [1–3]. The imperative for enhanced sanitation and wastewater treatment further amplifies this trend; while critical for safeguarding public health and the environment, these processes inevitably produce sludge as a byproduct [4]. According to reports, the annual generation of sewage sludge is distributed as follows: the United States with 4.96 million tons, India with 4.36 million tons, Japan with 2.2 million tons, and China with a significant 11.2 million tons [5]. The composition of sewage sludge is intricate and subject to variation based on factors such as waste type, treatment processes, seasonal changes, and geographical location [6]. The primary constituents, which include organic matter, inorganic particles, microorganisms, heavy metals, and colloidal substances, can pose risks to human health [7]. Currently, the predominant sludge treatment technologies encompass sludge dewatering, anaerobic digestion, high-temperature aerobic fermentation, hydrothermal carbonization, and thermal drying [8,9]. Among these, thermal drying stands out as an efficacious method for sludge management [10,11]. This technology not only

minimizes the sludge's volume and weight, but also facilitates energy recovery and reduced land usage, thereby improving resource utilization efficiency and adhering to sustainable development principles. Post-thermal drying, the sludge's water content is significantly reduced, enhancing its calorific value. The dried sludge is then conveyed to incinerators for combustion, where the heat generated can be harnessed for electricity production, heating, or various industrial applications.

However, due to its high moisture content, sewage treatment sludge cannot be directly incinerated and requires thermal drying treatment for beneficial utilization. Thermal drying was an intermediate step in sludge treatment [12,13]. This stage further reduced the moisture content of mechanically dehydrated sludge, meeting final disposal requirements and significantly lowering the content of hazardous substances [14,15]. The evaporation of moisture during the sludge drying process primarily involves the evaporation of free water on the sludge surface and the migration of intracellular-bound water to the sludge surface. In this process, free water quickly moved to the sludge surface and evaporated, but the interstitial and bound water required thermal energy to migrate to the surface. Generally, the longer the drying time, the more difficult it became to evaporate the moisture in the sludge (mainly interstitial and bound water at this stage), and the drying rate decreased. Many researchers have attempted to improve drying efficiency by incorporating specific additives [16,17]. For instance, Zhou et al. [18] discovered that co-application of lime significantly improved sludge dewaterability. Wu et al. [19] achieved improvement by mixing sludge particles with rice husk flour. Ge et al. [20] obtained favorable results by adding calcium peroxide to enhance the ketone peroxide process. Liu et al. [21] found that combining Fenton's reagent and calcium oxide effectively increased the water loss rate of sludge. Although these additives may alter solid properties and play other roles in the process, the specific mechanism of how calcium oxide influences sludge drying remains unclear [22].

Moreover, it was essential to address the emission of malodorous pollutants, particularly nitrogen- and sulfur-containing compounds, as they present significant environmental and public health challenges [23]. These emissions impeded the practical application of sludge thermal drying. Fan et al. [24] demonstrated that calcium oxide effectively inhibits the release of hydrogen sulfide, yet there was a lack of relevant literature describing the impact of calcium oxide on pollutant emissions.

This work investigated the drying of municipal sludge and pollutant release characteristics. Besides, the drying temperature, moisture content, and the influence of the calcium oxide ratio on sludge drying features and ammonia release characteristics were evaluated. This work provided necessary guidance on the sludge drying process by analyzing the changes in the physicochemical properties of sludge during drying. The relevant data could be used to promote the sludge drying process.

2. Experimental Section

2.1. Materials

The sludge samples (20 kg) used in the experimental study were obtained from a sludge treatment plant in Jiangsu (10 December 2023). After preliminary dewatering, the initial moisture content of the sludge was approximately 86%. Different proportions of calcium oxide were added to condition the sludge before conducting the drying experiments. Prior to the experiments, the samples were stored in a refrigerator at 5 °C. The industrial and elemental analysis of sludge mud was tested according to the GB/T 212-2008 proximate analysis of coal (Chinese standard), and the test results were presented in Table 1 [25].

Table 1. Results of industrial and elemental analysis of sludge.

Industrial Analysis */%			Elemental Analysis/%				
A _{ad}	V _{ad}	FC _{ad}	C	H	O	N	S
46.59	43.49	5.58	26.07	3.91	13.85	3.74	1.5

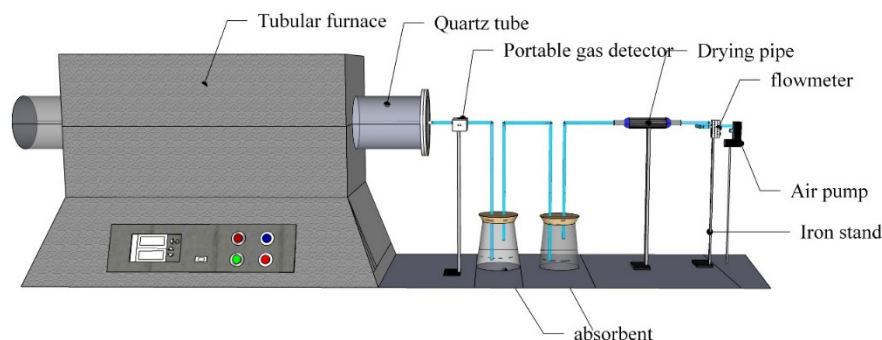
* A_{ad}: Ash on air-dried basis; V_{ad}: Volatile Matter on air-dried basis; FC_{ad}: Fixed Carbon on air-dried basis.

2.2. Analytical Method

This work conducted sludge drying experiments using a tubular furnace, as illustrated in Figure 1. To ensure uniform sample quality and heated surface area, the sludge was shaped into rectangular blocks (5 ± 0.05 g) with dimensions of 60 mm in length and 30 mm in width using ceramic membrane holders. Subsequently, these sludge blocks were placed in crucibles and inserted into the tubular furnace (Anhui Kemi Instrument, TFH-1200-50-440, Hefei, China). The carrier gas flow rate inside the quartz tube was maintained throughout the heating process at 2.5 L/min. The tubular furnace temperatures were set at 90, 120, 150, 180, and 210 °C, constituting five temperature conditions. Once temperature and airflow stability were achieved, 5 g of sludge was placed in the middle section of the tubular furnace. The calculation formula to define the relative moisture content of sludge w_t was as follows:

$$w_t = \frac{m_t - m_d}{m_0 - m_d} \quad (1)$$

where m_t was the sludge mass (g) at time t , m_d was the absolute dry sludge mass (g) at the end point of drying, and m_0 was the sludge mass (g) at the initial moment.

**Figure 1.** Experimental facility of sludge drying device.

The outlet of the tubular furnace was connected to a portable gas detector (Xinye environmental monitoring instrument, XY-500MS, Qiandao, China), drying tube, flowmeter, absorption bottle, and vacuum pump. The drying tube contained a silica gel and calcium oxide particles, capturing gaseous by-products such as NH_3 , H_2S , CO , and CH_4 . The release rates per unit were detected using a portable gas detector. Due to their low concentrations, these by-products, after simple processing, were directly discharged into the atmosphere. Repetitive experiments were conducted under all operating conditions to minimize errors.

3. Results and Discussion

3.1. Sludge Drying Characteristics

3.1.1. Sludge Drying Characteristics Without Calcium Oxide Addition

Figure 2 illustrated the variation in relative moisture content of the sludge. Notably, the drying time for the sludge at 90 °C was 200 min, whereas at 210 °C, the drying time was merely 40 min, representing an 80% reduction in time. This observation highlights that with increasing temperature, the drying efficiency of the sludge improved significantly, leading to a significant reduction in drying time. The increasing slope of the curves in the

figure with higher drying temperatures further corroborates this conclusion. Additionally, it was evident from the figure that as the temperature rises, the spacing between the curves noticeably narrows, indicating a reduced rate in the decrease of sludge drying time. It suggested that while elevating the drying temperature could continue to decrease the sludge drying time, it came at the cost of diminishing the overall effectiveness of sludge drying.

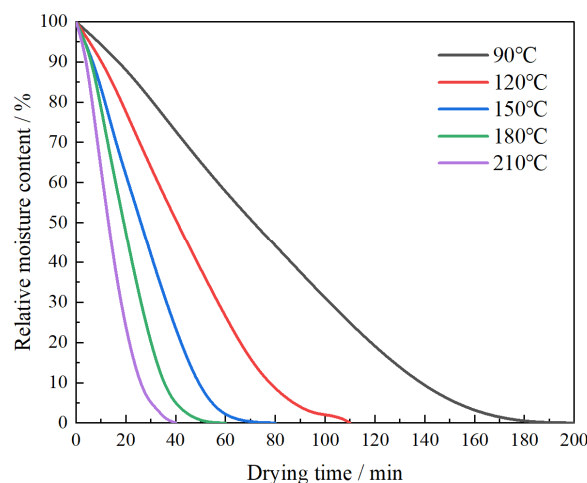


Figure 2. The relative moisture content of sludge at different drying temperatures.

In order to illustrate the drying characteristics of sludge more directly, the drying and dehydration rates of sludge were evaluated. The variation in sludge drying rate with moisture content was depicted in Figure 3a. In the initial stages of sludge drying, the drying rate rapidly peaks before gradually declining. As the sludge drying temperature escalated from 90 °C to 210 °C, the corresponding peak increased from 0.033 g/(g·min) to 0.2 g/(g·min). This phenomenon was attributed to the evaporation of free water within the sludge during the early drying stages. Higher temperatures enhanced the water evaporation process, consequently accelerating the drying rate. The trend of sludge drying rates with moisture content was consistent across different temperatures, indicating an initial increase followed by a decrease. The maximum drying rate was achieved at around 83% sludge moisture content, which could be attributed to the rapid removal of capillary and cellular water within the sludge.

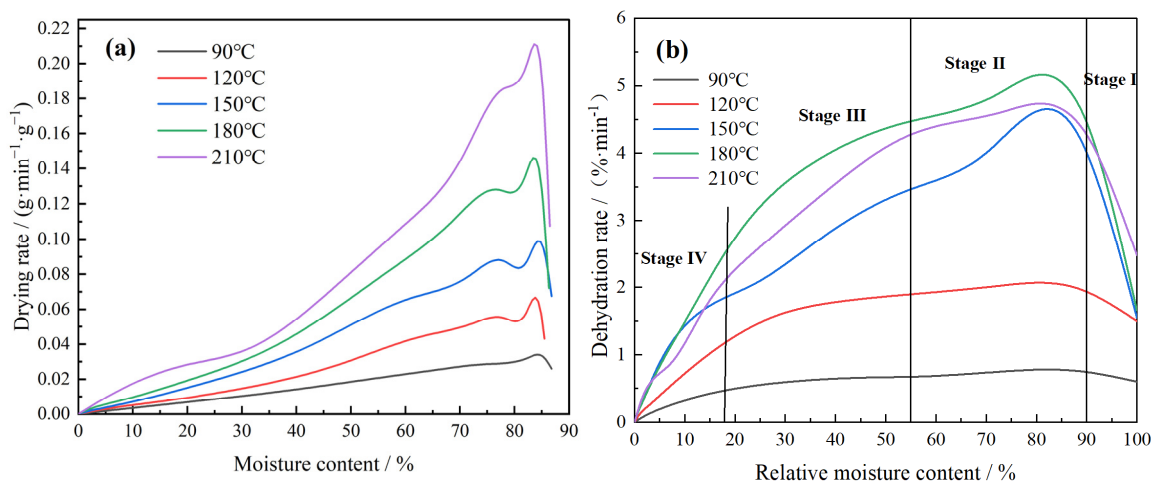


Figure 3. Drying characteristics of sludge at different drying temperatures. (a) Drying rate; (b) Dehydration rate.

The rate at which sludge dehydrates in correlation with its relative moisture content offers a novel perspective on the weight loss behavior throughout the sludge drying process. As illustrated in Figure 3b, an initial increase followed by a subsequent decrease in the sludge's dehydration rate was noted in tandem with a decrease in relative moisture content. This trend provides valuable insights into the dynamics of moisture removal during sludge drying. At drying temperatures of 90 °C and 120 °C, the curves remained relatively stable with minimal variations. As the temperature continued to rise, the curves exhibited increased variability and showed the emergence of peaks. This phenomenon may be attributed to the differentiation in moisture removal within the sludge as the drying temperature increased. In the early stages, the removal rate of free water was significantly higher than that of bound water in the later stages. Taking the drying curve of sludge at 180 °C as an example, Figure 3b revealed that the sludge drying process could be divided into four stages [26]. Stage I, the initial phase, involved preheating the sludge, during which a minor portion of free and surface water was evaporated. Stage II marked the rapid drying phase, distinguished by a significant rise in temperature, swift evaporation of surface and free water within the sludge, and a corresponding surge in the dehydration rate. Progressing to Stage III, the first deceleration phase of the sludge drying process, capillary water and adsorbed water became the predominant moisture sources for evaporation. Consequently, this led to a decline in the drying rate and an extension in the drying duration. It was attributed to the characteristics of capillary water and adsorbed water. Capillary water was the water bound between sludge particles or particle fissures due to capillary action. Adsorbed water was the water adsorbed on the surface of sludge particles due to surface tension. Because sludge particles were small and exhibited strong surface adsorption, these types of water were challenging to remove. Stage IV was the second deceleration drying stage and the concluding phase of the sludge drying process. At this point, the moisture in the sludge was nearly depleted. Further heating led to a slower increase in thermal stress between sludge particles, causing the sludge to crack. The internal water within the sludge particles and microorganisms was released [27].

3.1.2. Sludge Drying Characteristics with Calcium Oxide Addition

Calcium oxide, an essential solid alkaline substance, was crucial in sludge treatment. Its reaction with sludge induces multiple changes, encompassing physical, chemical, and environmental aspects. Firstly, due to its alkaline nature, incorporating calcium oxide into sludge can adjust the pH of the waste. This adjustment helps improve the acid–base balance of the sludge, mitigates the adverse effects of acidic waste on the environment, and creates more favorable conditions for subsequent treatment steps. Secondly, calcium oxide can facilitate moisture removal from the sludge, making it drier and denser. It could effectively reduce sewage sludge volume, easing subsequent disposal processes. Finally, calcium oxide possesses specific bactericidal and disinfectant properties, which can inhibit the proliferation of microorganisms in the sludge, reduce the generation of malodors, and improve the sludge treatment environment to some extent.

Figure 4a illustrates the drying rate of sludge with varying calcium oxide content and demonstrates a consistent trend with changes in water content. The drying rate initially increased and subsequently decreased with decreasing sludge water content. The maximum sludge drying rate was observed as $0.127 \text{ (g} \cdot \text{min}^{-1} \cdot \text{g}^{-1})$ without calcium oxide addition, $0.133 \text{ (g} \cdot \text{min}^{-1} \cdot \text{g}^{-1})$ with 5% calcium oxide, and $0.164 \text{ (g} \cdot \text{min}^{-1} \cdot \text{g}^{-1})$ with 15% calcium oxide. Upon adding 50% calcium oxide, the maximum drying rate reached $0.197 \text{ (g} \cdot \text{min}^{-1} \cdot \text{g}^{-1})$, reflecting increases of 1.05, 1.29, and 1.55 times, respectively. Figure 4b further demonstrated that an increase in the proportion of injected calcium oxide led to a gradual reduction in the drying time of sludge with the same mass, accompanied by

a decrease in sludge moisture content within the same time frame. This phenomenon can be attributed to the hindrance of water movement within the dense material of the original sludge during the drying process, as diffusion was impeded. Adding calcium oxide enhanced the sludge's hydrophilicity, hydration, and cohesiveness, causing the sludge to transform from a slurry to a semi-solid state with higher viscosity and eventually to a solid block. The sludge's drying rate in this transformation relied on water diffusion within the solid structure. Calcium oxide facilitated sludge cracking at a specific temperature, releasing cellular water as easily lost water. This increased the speed of water diffusion within the sludge, subsequently enhancing the sludge's drying rate. This observation aligns with the findings of Liu et al. [28]. The data presented indicated that adding varying proportions of calcium oxide can significantly improve the sludge drying rate.

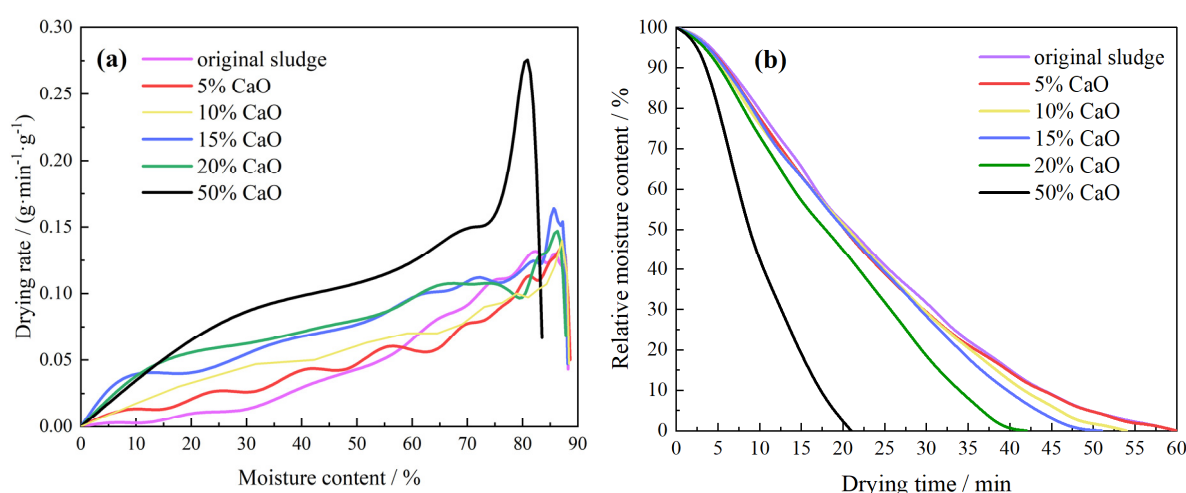


Figure 4. Drying characteristics of sludge with calcium oxide addition. (a) Drying rate; (b) Relative moisture content.

3.2. Gaseous Pollutant Release Characteristics

3.2.1. Emission of Gaseous Pollutants Without Calcium Oxide Addition

Figure 5a illustrates the variation in ammonia release with drying time across temperatures ranging from 90 to 210 °C. The trend observed indicated an initial increase followed by a subsequent decrease in the release of ammonia gas over time at different temperatures. At 90 °C, the maximum release of ammonia reached 22.3 ($\text{mg} \cdot \text{m}^{-3} \cdot \text{g}^{-1}$), occurring after 10 min of drying, with a continuous production time of 60 min. Conversely, at 210 °C, the peak release of ammonia, which reached 73.4 ($\text{mg} \cdot \text{m}^{-3} \cdot \text{g}^{-1}$), occurred after 6 min of drying and decreased during the subsequent 15-min production time. The maximum release of ammonia gas at 210 °C was 3.3 times that at 90 °C, while the production time was only 0.25 times that at 90 °C. These findings indicated that ammonia production primarily occurred in the early stages of sludge drying, where it can dissolve into the free water, capillary water, and adsorbed water within the sludge due to its high water solubility. Throughout the degradation process, continuous generation of fatty acids and carbon dioxide occurs, converting a significant amount of ammonia into non-volatile ammonium ions. Ultimately, ammonia predominantly exists as ammonium bicarbonate in the sludge. Notably, ammonium bicarbonate exhibits poor thermal stability and undergoes decomposition at 35 °C. As the drying temperature elevates, the decomposition rate of ammonium bicarbonate intensifies, curtailing the duration of ammonia emission and amplifying the quantity released. This pattern is in accordance with the research conducted by Wang et al. [29]. Moreover, the findings indicate that the peak emission amounts of ammonia at 90 °C and 120 °C are essentially equivalent; however, the sustained generation period of ammonia at

120 °C is nearly one-third shorter than at 90 °C. Therefore, opting to conduct the sludge drying process at 120 °C could significantly reduce ammonia generation, aligning with the optimization of the drying process for environmental and operational efficiency.

As observed in Figure 5b, when the drying temperature increased to 180 °C, H₂S production commenced, and the unit release of hydrogen sulfide exhibited an overall trend of initial increase followed by a subsequent decrease. At 180 °C, hydrogen sulfide began to be generated after 40 min of drying, reaching its maximum unit release of 0.016 (mg·m⁻³·g⁻¹) within 20 min. Upon further increasing the temperature to 210 °C, the unit release of hydrogen sulfide significantly increased, and the release time was notably advanced, with the maximum unit release being approximately three times that at 180 °C. It may be attributed to the fact that with the temperature rise, some inorganic sulfides in the sludge during the drying process undergo thermal decomposition, transforming into hydrogen sulfide and being released, leading to an elevated concentration of hydrogen sulfide [30]. It was also noteworthy from the figure that the unit release of hydrogen sulfide was unstable, which may be attributed to changes in the sludge's morphology during the drying process. Fractures throughout the sludge during drying induce uneven heating, causing fluctuations in the rate of sulfide decomposition. Thus, to minimize the release of hydrogen sulfide, it was advisable to control the drying temperature below 180 °C.

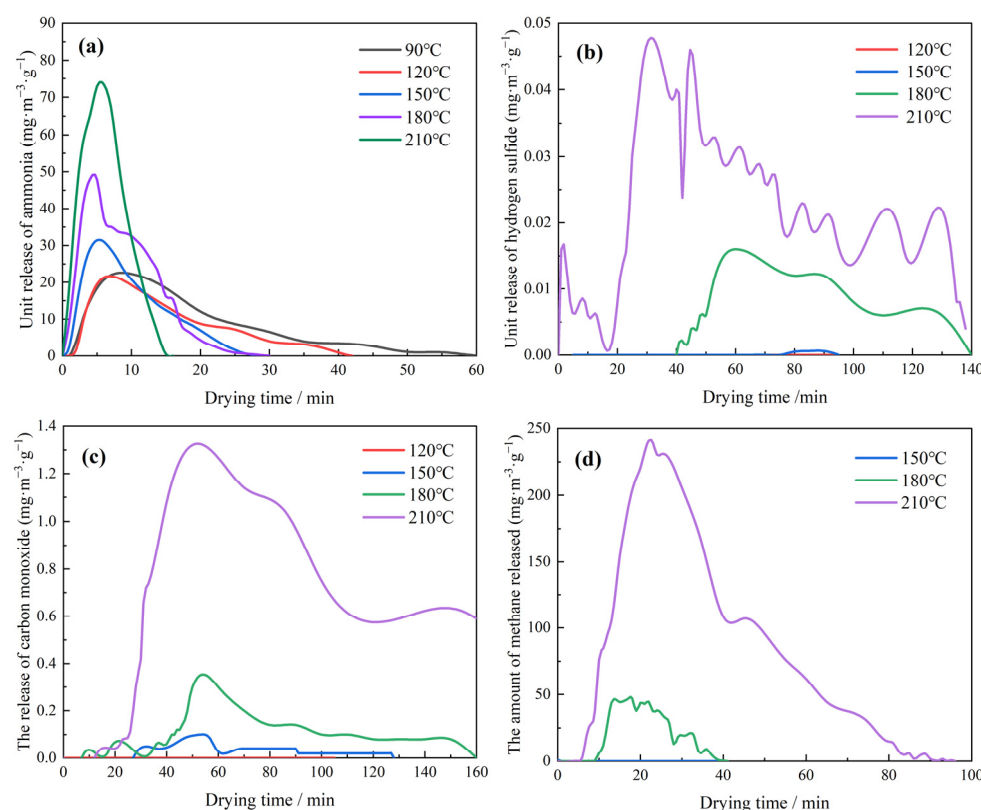


Figure 5. Emission of gaseous pollutants without calcium oxide addition. (a) ammonia; (b) hydrogen sulfide; (c) carbon monoxide; (d) methane.

As depicted in Figure 5c, carbon monoxide began to appear at 150 °C, and with increasing temperature, the unit release of carbon monoxide exhibited an initial rise, followed by a subsequent decline to a plateau before continuing to decrease to zero. As the temperature increased from 150 °C to 210 °C, the maximum unit release of carbon monoxide increased from 0.11 (mg·m⁻³·g⁻¹) to 1.35 (mg·m⁻³·g⁻¹), approximately 13 times higher. It indicated that the unit release of carbon monoxide increases with temperature elevation. It was generally acknowledged that carbon monoxide generated during the sludge drying process

primarily originates from the cleavage of oxygen-containing functional groups (such as carbonyl, carboxyl, and ether bonds) in some organic compounds, as well as the secondary cleavage of compounds containing hydroxyl groups and oxygen-containing heterocyclic compounds. Given the significant health risks posed by carbon monoxide, controlling the temperature below 150 °C during sludge drying in engineering applications can effectively prevent the generation of carbon monoxide. As illustrated in Figure 5d, methane generation commences at 180 °C, reaching a maximum unit release of $48(\text{mg}\cdot\text{m}^{-3}\cdot\text{g}^{-1})$. With the temperature elevation, the maximum unit release rapidly increased to $241(\text{mg}\cdot\text{m}^{-3}\cdot\text{g}^{-1})$, approximately a fivefold enhancement. It was because methane in sludge predominantly arose from the cleavage of side chains in organic volatile fractions. As the temperature further increased, these side chains' cleavage intensified, leading to a higher unit release of methane. It was advisable to consider controlling the temperature below 180 °C during the sludge drying to mitigate methane emissions.

3.2.2. Emission of Gaseous Pollutants with Calcium Oxide Addition

In order to investigate the influence of calcium oxide on various gaseous pollutants, sludge drying experiments were conducted at 180 °C. The experiments revealed that adding different proportions of calcium oxide had minimal impact on releasing methane and carbon monoxide, as shown in Figure 6a,b. Figure 6c illustrates the variation in the unit release of ammonia over time after the addition of calcium oxide in sludge. It can be observed that when the proportion of added calcium oxide was 5%, 20%, and 50%, the maximum release of ammonia was higher than that without calcium oxide, increasing by 10.34%, 3.15%, and 33.71%, respectively. When the addition ratio was 10% and 15%, the maximum release of ammonia was lower than that without calcium oxide, decreasing by 1% and 18.38%, respectively. This may be attributed to the denaturation of proteins in the sludge and the hydrolysis to produce amino acids after adding calcium oxide, and amino acids, along with some lipid products, which can undergo a series of chelation and complexation reactions with calcium ions, resulting in the precipitation of calcium glutamate [11,31]. This indicated that adding a certain proportion of calcium oxide in the sludge could effectively inhibit ammonia generation. Additionally, it can be observed from the graph that as the proportion of added calcium oxide increased, the duration of continuous ammonia release decreased, and the time to reach the maximum release was advanced. This may be due to the reaction between calcium oxide and free water in the sludge after the addition of calcium oxide, promoting the early release of ammonia dissolved in the sludge. The results suggested that controlling the mixture ratio of calcium oxide in the 10% to 20% range could effectively reduce the unit release of ammonia.

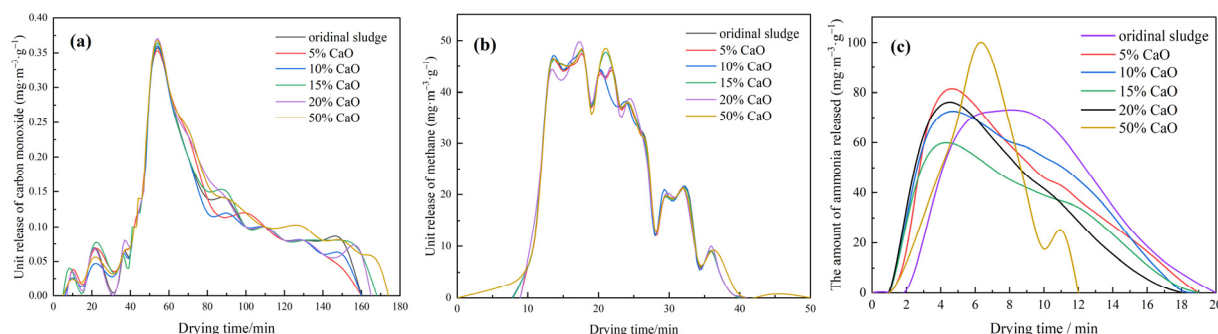


Figure 6. Emission of gaseous pollutants after calcium oxide addition. (a) carbon monoxide; (b) methane; (c) ammonia.

3.3. Sludge Characteristics After Drying

3.3.1. Sludge Drying Without Calcium Oxide Addition

Figure 7 presents the SEM images of sludge after drying at different temperatures. At 90 °C, the surface particle clusters of the sludge appeared relatively smooth, forming a spherical state with only a few cracks. Consequently, the sludge drying rate was relatively slow. As the temperature increased to 150 °C, the surface of the sludge particle clusters began to exhibit larger pores, and the degree of fracturing intensified with a significant increase in the number of pore channels. Upon reaching 210 °C, the sludge displayed a clear network pattern, indicating a substantial increase in pore channels. The quantity of pore channels was closely related to the evaporation of water during the sludge drying process.

The BET results corroborated the alterations in sludge pore channels. As presented in Table 2, the elevation of the drying temperature from 90 °C to 150 °C corresponded to a gradual increase in the specific surface area and a reduction in pore radius. It suggested a continuous augmentation in the number of tiny pores within the sludge. Theoretically, a smaller pore radius would result in a smaller pore volume. However, the pore volume increased under these conditions, indicating that some pores had folded or collapsed, leading to the fusion of specific pores into larger ones. The pore radius expanded with the temperature, further rising to 210 °C, yet the specific surface area diminished. This indicated an intensified collapse degree and an escalation in the number of large pores at this point, consequently accelerating the drying rate of the sludge.

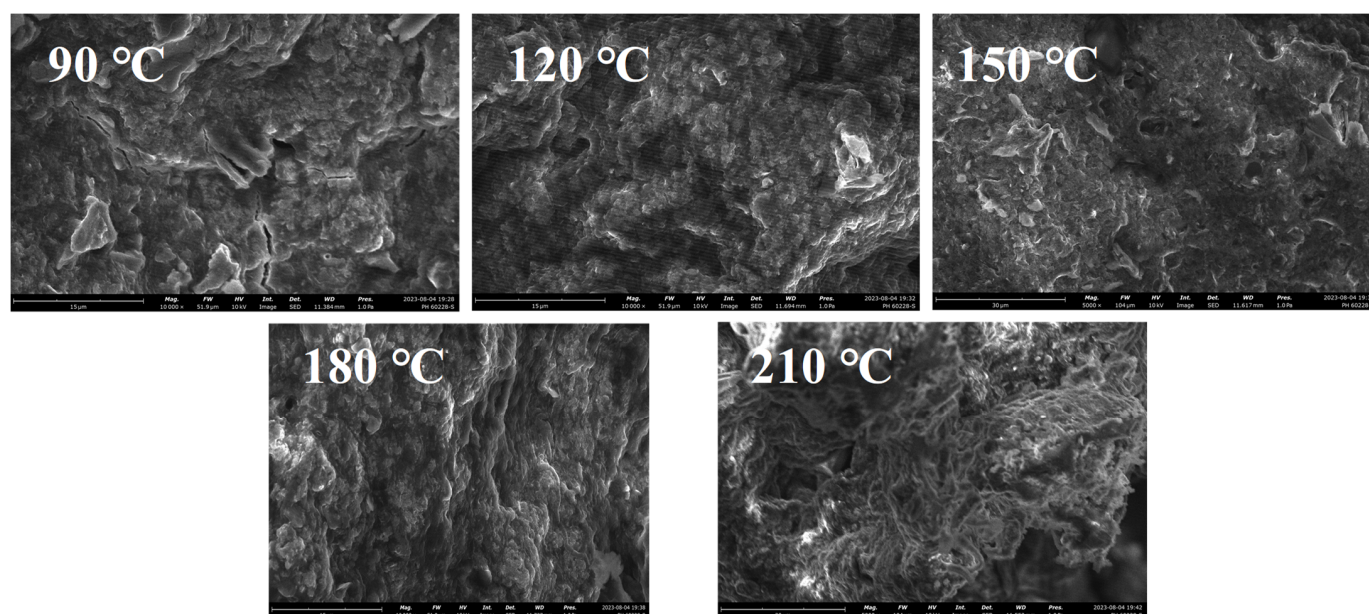


Figure 7. SEM images of sludge after drying.

Table 2. BET characterization results of sludge drying at different temperatures.

Drying Temperature/°C	Specific Surface Area/m ² ·g ^{−1}	Pore Volume/cm ³ ·g ^{−1}	Hole Radius/nm
90	14.053	0.059	39.665
120	14.149	0.061	39.581
150	15.980	0.061	39.366
180	12.396	0.051	39.412
210	11.969	0.049	48.753

3.3.2. Sludge Drying with Calcium Oxide Addition

Figure 8b showed that when the proportion of calcium oxide was 5%, the sludge started to loosen and exhibited a chain-like structure, compared with no calcium oxide

addition (Figure 8a). At this point, large pores appeared on the sludge surface, enhancing the drying rate. When the addition of calcium oxide was 10% and 15%, as depicted in Figure 8c,d, the surface structure of the sludge collapsed, presenting loose spherical particles and condensing into clusters with a flowered morphology. Besides, surface pore channels increased, further improving the sludge drying rate. As shown in Figure 8e,f, when the proportion of calcium oxide reached 20% and 50%, the clusters of flower-shaped structures began to consolidate at the center, exhibiting an octopus-like configuration. The number of pore channels significantly decreased, resulting in a substantial reduction in the sludge drying rate. However, there was a notable difference from the results above. This discrepancy arises from the reaction between calcium oxide and water, accelerating water evaporation, thereby enhancing the sludge's drying rate in the early drying phase.

Table 3 presented the BET characterization outcomes following the drying of sludge at 180 °C with the addition of calcium oxide. Incorporating 5% calcium oxide into the sludge not only augmented the specific surface area of the sludge but also increased the radius of the pore channels, resulting in a significant enhancement in sludge drying efficiency. As the calcium oxide proportion rose to 15%, there was a decrease in the specific surface area of the sludge, an increase in the pore radius, and a reduction in pore volume. Moreover, small pores fused into larger ones, further improving sludge drying efficiency. With calcium oxide proportions of 20% and 50%, the sludge's specific surface area and pore radius continued to decrease, leading to a continuous decline in sludge drying efficiency, aligning with the findings mentioned above.

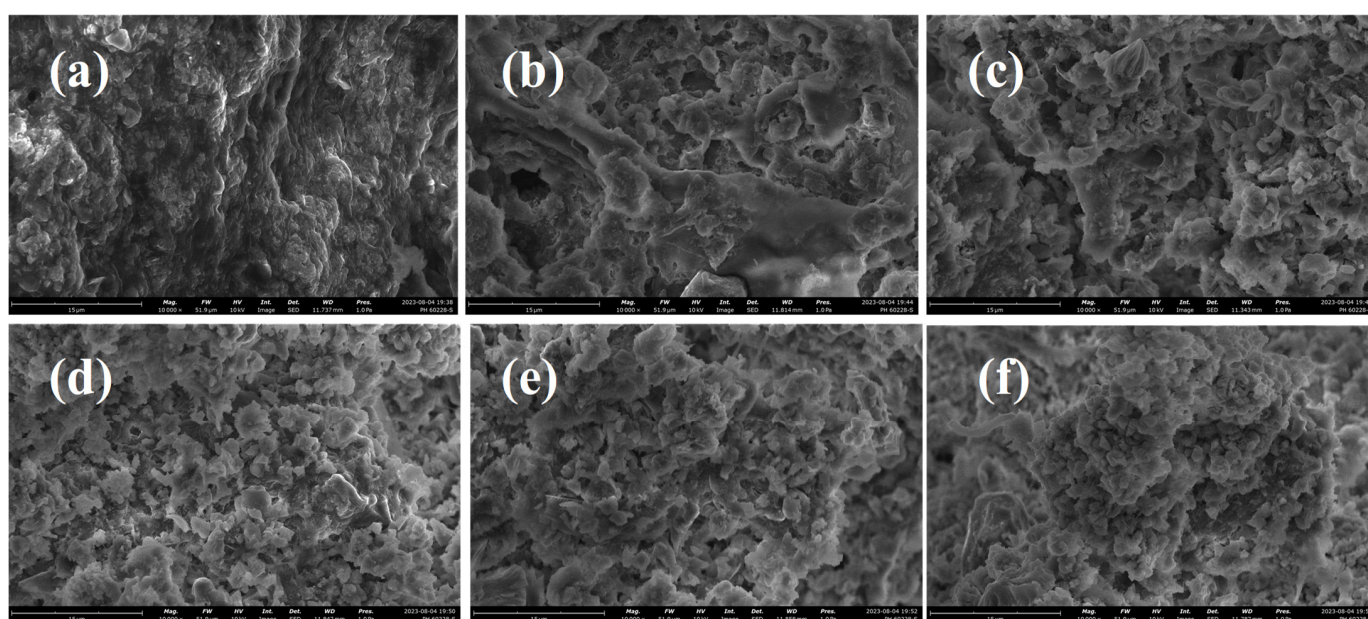


Figure 8. SEM images after drying of sludge with different proportions of calcium oxide at 180 °C. (a) Without calcium oxide addition; (b) 5% calcium oxide addition; (c) 10% addition; (d) 15% addition; (e) 20% addition; (f) 50% addition.

Table 3. BET characterization results of sludge drying after adding calcium oxide at 180 °C.

Calcium Oxide Addition Ratio/%	Specific Surface Area/m ² ·g ^{−1}	Pore Volume/cm ³ ·g ^{−1}	Hole Radius/nm
0	12.396	0.051	39.412
5	28.577	0.109	63.040
10	23.238	0.082	62.641
15	17.892	0.063	63.38
20	17.326	0.051	19.12
50	8.788	0.023	19.019

4. Conclusions

As China's economy experiences rapid growth, there is a concurrent increase in the efficiency of urban sewage and industrial wastewater treatment, leading to a substantial rise in the generation of sludge. The thermal drying process is crucial for the volume reduction, secure disposal, and beneficial use of sludge. Nevertheless, the drying process inevitably emits harmful pollutants, which present latent environmental hazards that require vigilant control measures to mitigate associated risks. The conclusions of this paper are as follows.

- (1) The higher temperatures led to a faster sludge drying rate, accelerated water evaporation, and reduced drying time. However, with the increase in temperature, the types and release amounts of gaseous pollutants also escalated. Therefore, maintaining the temperature within the 120–180 °C range was considered more reasonable.
- (2) Online detection of NH₃, H₂S, CO, and CH₄ in the exhaust gas revealed that pollutant generation is temperature-dependent. The addition of a certain proportion of calcium oxide had no significant effect on CH₄ and CO emissions, but it exhibited a noticeable inhibitory effect on the generation of H₂S and NH₃ to some extent.
- (3) Introducing a certain proportion of calcium oxide into the sludge effectively enhanced the drying efficiency of the sludge and reduced the release of pollutants. However, this approach also increased the content of solid products, thereby raising the subsequent processing costs and complexities. Thus, it was optimal to control the mixed ratio of calcium oxide within 5–15%.

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