Investigation of the effects of temperature and sludge characteristics on odors and VOC emissions during the drying process of sewage sludge

Wenjie Ding, Lin Li and Junxin Liu

ABSTRACT

Sludge drying is a necessary step for sludge disposal. In this study, sludge was collected from two wastewater treatment plants, and dried at different temperatures in the laboratory. The emission of odor and total volatile organic compounds (TVOCs) during the sludge drying process were determined by an online odor monitoring system. The volatile organic compounds (VOCs) in off-gas were analyzed by gas chromatography–mass spectrometry. Results showed that sludge with 30% moisture content could be obtained in 51 minutes under drying temperature 100°C but only within 27 minutes under 150°C. Concentration of odor, TVOCs, sulfur-containing compounds (SCCs), and amines were changed with drying temperature and sludge sources. The maximum concentration of odor, TVOCs, SCCs, and amines were 503.13 ppm, 3.01 ppm, 8.15 ppm, and 11.27 ppm, respectively, at drying temperature 100°C. These values reached 1,250.79, 8.10, 53.51, and 37.80 ppm when sludge dried at 150°C. Odor concentration had a close relationship with emission of SCCs, amines, and TVOCs. The main VOCs released were benzene series and organic acid. Potential migration of substances in sludge was examined via analysis of off-gas and condensate, aiming to provide scientific data for effective sludge treatment and off-gas control.

Key words | emission, odor, sludge characteristics, sludge drying, VOC

ABBREVIATIONS

TVOCs total volatile organic compounds
VOCs volatile organic compounds
SCCs sulfur-containing compounds
GBP wastewater treatment plant named GBP
XHP wastewater treatment plant named XHP
GBPS sludge from GBP
XHPS sludge from XHP
GBPS-D dried sludge of GBP
XHPS-D dried sludge of XHP
GBPS-odor Odor concentration released during drying process of GBPS
XHPS-odor Odor concentration released during drying process of XHPS
GBPS-SCCs concentration of sulfur-containing compounds released during drying process of GBPS
XHPS-SCCs concentration of sulfur-containing compounds released during drying process of XHPS
GBPS-Amines concentration of amines released during drying process of GBPS
XHPS-Amines concentration of amines released during drying process of XHPS
GBPS-TVOCs concentration of total volatile organic compounds released during drying process of GBPS
XHPS-TVOCs concentration of total volatile organic compounds released during drying process of XHPS

DT drying temperature
TD time duration of drying process
MC moisture content
MCR moisture content range
DRM decreasing rate of moisture content
TOC total organic carbon
DOM dissolved organic materials

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INTRODUCTION

Over 3,000 wastewater treatment plants (WWTPs) have been built in China, and the total treatment capacity reached up to 145 million m³ per day at the end of 2013. With the increasing number of sewage treatment plants, production of sewage sludge with 80% moisture content from these plants will reach up to 33.59 million tons in 2015. Sludge contains a large amount of moisture, organic matter, and inorganic salt. It also contains many hazardous substances such as pathogens, which pose a threat to the ecological environment and to human health. Sanitary landfill, compost, and incineration are the three main methods for sludge treatment. Compared with sludge compost and sludge landfill, sludge incineration is a more effective and reliable technology because such a method reduces sludge volume and pathogens; sludge incineration also destroys toxic organic compounds and recovers dry sludge. A cost-combined life-cycle assessment was conducted to estimate the environmental and economic burdens of 13 sewage sludge-treatment scenarios in China; results showed that incineration had the lowest environmental burdens (Xu et al. 2014).

The moisture content of the sludge produced from sewage treatment plants is usually around 80%, which cannot be directly incinerated. Thus, the moisture content should be reduced to below 50%. Thermal drying is an effective method for sludge desiccation. Sludge drying technology uses heat to sterilize the sludge and destroy its gel structure. The temperature reaches up to 95 °C to kill the pathogen, which can significantly minimize the volume of the sludge. Sludge drying has been widely applied in Europe for over 20 years, particularly in Germany where dried sludge is frequently used in coal-fired power stations and cement kilns (Kelessidis & Stasinakis 2012; Li et al. 2013; Remy et al. 2013). During the sludge drying process, approximately 81% of the energy invested in the drying process is extracted in the dried sludge product (Rodriguez et al. 2013). However, large amounts of odors and volatile organic compounds (VOCs) are generated and released during the sludge drying process. These odors and VOCs are mainly composed of nitrogen-containing compounds and sulfur-containing compounds (SCCs). The VOCs include aromatic compounds, organic acids, aldehydes, alcohols, ethers, and indoles, which may cause odorous pollution that is extremely harmful to the ecological and living environments. VOC emissions have been investigated during the sewage sludge drying process at different temperatures, and 45 compounds from the emissions have been identified (Gomez-Rico et al. 2008).

A laboratory-scale tubular drying furnace and a pilot-scale paddle dryer were used for sludge drying to observe the release of VOCs (Deng et al. 2009). The results showed that CO₂, NH₃, C₇H₁₆, volatile fatty acids, and CH₄ were frequently present during the drying process. NH₃ was the dominant pollutant, which could reach up to 170 mg/Nm³. A novel system combining sludge drying and co-combustion with coal was applied in disposing sludge, and the atmospheric emission characteristics of this system were tested (Lu et al. 2013). The emission was composed of SO₂, NO, NO₂, NH₃, and CH₄ with corresponding concentrations of 240, 67.5, 5.98, 4,187, and 2.67 mg/m³.

The composition and level of emissions relied on the drying temperature, source of sludge, and processing time (Gomez-Rico et al. 2008; Weng et al. 2012). Weng et al. (2012) reported that 4.20–161.90 μg/m³ of total BTEX was generated when the drying temperature ranged from 50 to 300 °C. The sludge from different wastewater treatment plants was compared, and the emission rate of BTEX was found to depend on the drying temperature.

Previous studies mainly focused on equipment design (Leonard et al. 2008), drying efficiency, energy recovery (Bennamoun et al. 2013), and VOC emission (Wang et al. 2007; Gomez-Rico et al. 2008; Deng et al. 2009; Weng et al. 2012). The odors produced during the drying process and their relationship with substances in sludge were still insufficient, which should elicit much attention.

In the present work, the emission levels of odors and VOCs from sludge drying were detected by an online odor monitoring system, which can conveniently observe the variation of odors. This study aimed to: (1) investigate the emission characteristics of SCCs, amines, and total volatile organic compounds (TVOCs), as well as the influence of sludge from different WWTPs; and (2) examine mass transfer between the sludge and emissions to provide scientific data for effective sludge treatment and control of odors and VOC emissions.

METHODS

Experimental set up

The sludge drying system consists of three parts: thermal drying, temperature controlling, and gas monitoring systems (Figure 1). The sludge was dried in a tubular resistance furnace that is 20 cm in length and 7 cm in diameter. The drying temperature was regulated by a thermocouple...
temperature sensor. The wet sludge was fed to the dryer via batch feeding. After weighing, sludge was put in the wet sludge storage pipe, which was installed in the tubular resistance furnace. When the drying test was finished, the dried sludge was taken out and the new wet sludge was added in to carry out the next test.

The sludge for the drying test was collected from two wastewater treatment plants, GBP and XHP. GBP was operated by traditional activated sludge process, and the daily treatment capacity was one million cubic metres of wastewater. XHP was operated in an Anaerobic–Anoxic–Oxic process with wastewater treatment capacity of 0.6 million m$^3$/d. Domestic wastewater was treated in GBP and a mixture of industrial and domestic wastewater (the ratio was about 1:3) was treated in XHP. Centrifugal dried and belt filter were the sludge dewatering methods adopted by GBP and XHP, respectively. The sludge from GBP was designated GBPS and that from XHP was XHPS.

In terms of heat and mass transfer, the methods of sludge drying can be classified as direct drying and indirect drying. The indirect drying system was adopted in the present study because of its minimal vapor production and easy control.

**Analytical methods**

The level of odors, SCCs, amines, and TVOC emissions were monitored online by the odor monitoring system (Odor Catch/SLC-1205OP1240N01, Korea). Semiconductor gas sensors were installed in the instrument for odor, SCC, amine, and TVOC analyses. The VOCs, such as benzene, xylene, and organic acid, were analyzed by gas chromatography–mass spectrometry (GC-MS-QP2010 Shimadzu, Japan) equipped with a thermal desorption instrument (ATDS-3400A, China). The VOCs were collected via a Tenex-TA adsorption tube. Helium was used as carrier gas (constant flow rate: 1.5 mL/min). A DB-624-30M capillary column (60 m × 0.25 mm × 0.25 μm) was used for separation. The temperature of the inlet was 250 °C. The gaseous samples were manually injected, and the split ratio was 20:1. The temperature program of the capillary column was as follows: 38 °C held for 1.8 minutes; increased at 10 °C/min to 120 °C; increased at 15 °C/min to 210 °C and held for 10 minutes. The mass spectrometer was operated in electron ionization mode with electron energy of 70 eV.

The temperature of the tube-type resistance furnace (XY-RL, China) was controlled by a thermocouple (WRET-01, China). Water, VOC, and ash contents in the sludge were analyzed by gravimetric method. The chemical oxygen demand (COD) of the sludge was determined by a spectrophotometer (DR2800, Hach, USA) after digesting in the COD digestion tube (Hach, USA) according to the previously described method (Sophonsiri & Morgenroth, 2004).

To study the relation between sludge composition and odor emission, compounds in the sludge, including total organic carbon (TOC), protein, polysaccharide, and dissolved organic matter (DOM), were periodically analyzed. C, N, and S were analyzed by Vario EL III (Vario EL III, Germany). Kjeldahl apparatus (UDK152, Italy) was applied in protein determination. Polysaccharide content was analyzed by Dubois method (Dubois et al., 1956). A solid TOC analyzer (TOC-V CPH, Shimadzu, Japan) was used for TOC analysis, whereas 3D fluorescence spectrometry (F-4600 FL Spectrophotometer, Japan) was applied to determine the DOM.

\[ \text{NH}_4^+, \text{NO}_3^-, \text{NO}_2^-, \text{SO}_4^{2-}, \text{CO}_3^{2-} \] in the condensate were analyzed by ion chromatography (DIONEX, ICS1000, USA). The TOC in the condensate was detected by the TOC analyzer (Shimadzu TOC-V CPH, Japan).

**RESULTS AND DISCUSSION**

**Moisture content variation under different processing temperatures**

Two drying temperatures, 100 and 150 °C, were compared in this study.

The variation of moisture content in the two sludge samples used was investigated by changing the drying temperature and processing time. The results were obtained by carrying out a series of tests using the same batch of sludge collected from the same WWTP. The processors of the series of tests were as follows: after weighing, the sludge was added to the storage pipe and dried by resistance
furnace at a certain drying temperature (such as 100°C), then the wet sludge was taken out to determine the moisture content by gravimetric method after a certain drying time (such as 10 minutes). The moisture content of the sludge gradually reduced with processing time (Figure 2).

When the sludge dried up at 100°C, the moisture content dropped from 80% to below 7.06% in 60 minutes, whereas it reduced to 3.11% within 40 minutes at drying temperature of 150°C. A higher drying temperature indicates a more rapid decrease of the moisture content.

At 100°C drying temperature, the moisture content in XHPS declined at a rate of 0.51% per minute within the first 30 minutes. Subsequently, the rate increased to 1.55% per minute. While drying at 150°C, the moisture content reduced at a rate of 0.76% per minute within the first 10 minutes, which was greater than that when drying at 100°C. In the next 10 minutes, the rate of moisture content reduction reached 1.82% per minute. This rate then increased to 5.02% per minute. The moisture content in GBPS declined in a similar trend with that in XHPS during the drying process (Table 1).

The high rate of moisture content reduction could be achieved under high drying temperature, indicating that improved processing temperature promotes the drying rate of the sludge.

In most cases, the sludge moisture content must be ≤30% before incineration. About 30% of the moisture content could be reached within 27 minutes under a drying temperature of 150°C, whereas it needed 51 minutes when the drying temperature was 100°C in the present study.

**Odors and VOC emission during drying process**

Thermal drying of sludge led to odors and release of VOC with water vapor. Under a drying temperature of 100°C, XHPS was used to study how the concentrations of odor, SSCs, amines, and TVOCs changed with the processing time (Figure 3).

SSCs, amines, and TVOCs could be detected after 5 minutes. They gradually increased with the extension of drying time. Sharp increases of concentrations could be observed in sulfide and amine emissions when the sludge had been dried within 9 minutes, and both emissions reached the

![Figure 2](image-url)  
**Figure 2** | Moisture content in XHPS during drying processes.

![Figure 3](image-url)  
**Figure 3** | Odor concentration and VOC emission at drying temperature of 100°C.

<table>
<thead>
<tr>
<th>Sludge</th>
<th>DT/°C</th>
<th>TD/min</th>
<th>MCR/%</th>
<th>DRM/min (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XHPS</td>
<td>100</td>
<td>0–20</td>
<td>84.45–77.67</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>20–30</td>
<td>77.67–69.02</td>
<td>0.83</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30–40</td>
<td>69.02–53.51</td>
<td>1.55</td>
<td></td>
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<tr>
<td></td>
<td>40–50</td>
<td>53.51–32.57</td>
<td>2.09</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50–60</td>
<td>32.57–7.06</td>
<td>2.55</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>0–10</td>
<td>84.45–79.90</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td>79.90–61.82</td>
<td>1.82</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20–30</td>
<td>61.82–26.66</td>
<td>5.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30–40</td>
<td>26.66–3.11</td>
<td>5.87</td>
<td></td>
</tr>
<tr>
<td>GBPS</td>
<td>100</td>
<td>0–20</td>
<td>86.28–78.37</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>20–30</td>
<td>78.37–71.02</td>
<td>0.74</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30–40</td>
<td>71.02–55.56</td>
<td>1.55</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40–50</td>
<td>55.56–33.69</td>
<td>2.18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50–60</td>
<td>33.69–9.16</td>
<td>2.45</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>0–10</td>
<td>86.28–78.89</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td>78.89–58.45</td>
<td>2.04</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20–30</td>
<td>58.45–27.06</td>
<td>3.14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30–40</td>
<td>27.06–4.86</td>
<td>2.22</td>
<td></td>
</tr>
</tbody>
</table>

DT: drying temperature; TD: time duration of drying process; MCR: moisture content range; DRM: decreasing rate of moisture content.
maximum at a processing time of 19 minutes. At that time, the moisture content of the sludge was 77.99%. The maximum concentrations of sulfide and amines were 8.15 ppm and 11.27 ppm, respectively. These concentrations began to reduce synchronously. Unlike sulfide and amines, the concentration of TVOCs changed in volatility with multiple peaks, and the maximum value was 3.01 ppm, which was achieved at 34 minutes of processing time with sludge moisture content of 62.81%.

Notably, the odor concentration increased with the generation of SCCs and amines. The maximum value (503) was also detected within 19 minutes of processing time. When the concentrations of SCCs and amines changed, the odor concentration varied accordingly, indicating that the odor concentration had a strong correlation with SCCs (0.98, \(P < 0.05\)) and amines (0.97, \(P < 0.05\)). Although the variation of TVOCs was not similar to that of odor, the TVOCs also contributed to the odor concentration.

Factors affecting odor and VOC emissions

Processing temperature

The species and proportion of the released odors and VOC depended on the processing temperature and the sludge sources. Figure 4 shows the alteration of odor and TVOC emission levels during the drying process under 150 °C. Similarly, the level of emissions increased with time and started to decline after reaching a peak value. The maximum values of SCCs, amines, and TVOCs were 53.51 ppm, 37.8 ppm, and 8.1 ppm, respectively. The corresponding durations were 18, 17, and 16 minutes.

When the sludge (XHPS) was processed at 150 °C, the emission level was much higher than that at 100 °C, which resulted in higher odor concentration. The higher drying temperature led to the higher emission concentration of the pollutants. A similar phenomenon was reported by Deng et al. (2009) when they investigated the VOC released during the sludge drying process under 140–170 °C. High drying temperature accelerated not only the dewatering rate (Figure 2), but also the decomposition rate of organic substances. The concentrations of amines and SCCs increased because of protein decomposition when the sludge dried at 150 °C (Anderson et al. 2002). In contrast to drying at 100 °C, the odor concentration varied in accordance with sulfide, amine, and TVOC emission levels, and was affected by their mixture when the sludge was dried at 150 °C.

The compositions of the VOC produced in the sludge (XHPS) drying process under 100 and 150 °C were analyzed by GC-MS (Figure 5).

When the sludge was dried at 100 °C, the main ingredients in the VOC included benzene series, organic acid, and alcohol, which accounted for 75%, 17%, and 8%, respectively. Benzene series, organic acid, organic sulfide, and ketones were detected from the air stream generated during the drying process at 150 °C, which accounted for 52%, 33%, 11%, and 4%, respectively. Both the species and the level of the VOC were increased compared with those released during the drying process at 100 °C. The VOC emission is in control of the drying temperature, which was consistent with previous reports. Weng et al. (2012) observed that the pollutant emission rate significantly accelerates after the drying temperature exceeds 150 °C, whereas only 5.09% of the total emission is collected below 100 °C.

Previous studies have shown that during sludge thermal drying at 100 °C, the main ingredients in releasing gas included chain alkanes, which accounted for 80.90%, followed by aromatic hydrocarbon and naphthene with 9.65% and 5.27%, respectively. When the drying temperature was increased up to 150–250 °C, the chain alkanes and aromatic hydrocarbons were also the main components of the released gas. However, their proportions significantly changed. The differences in VOC species and proportions were probably attributed to the dissimilar sludge composition.

The large portion of sludge solids contained organic compounds and a complicated mixture of bacteria, viruses, protozoa, and other micro-organisms. VOCs such as benzene (0.47 mg/kg) and \(o\)-xylene (2.01 mg/kg) could also be
determined from the sludge containing 80% moisture content in the present study. These VOCs were released with vapor from the sludge to the air at the initial stage of sludge drying. Subsequently, macromolecular organic substances, such as proteins and carbohydrates, started to break down and formed low molecular organic compounds and other products (Ferrasse et al. 2003). The emission of volatile products led to the formation of another maximum value. Therefore, the TVOCs released more than one peak in the drying process, particularly under lower processing temperature.

**Source of excess sludge**

Sludge samples used were compared at the same processing temperature (100 °C) to investigate the influences of sludge components on odor and VOC emission. The concentrations of sulfide and amines, as well as odor released from GBPS and XHPS, reached the peak simultaneously (Figure 6).

Multiple peaks were observed in the emission of TVOCs. The levels of odor and VOC generated from GBPS were higher than those released from XHPS under the same drying temperature. Sludge from wastewater treatment plants contains a complicated mixture of inorganic particles and organic matter. The water quality, wastewater treatment process selected, and the operation parameters influence sludge composition, thereby affecting the level of odor concentration and composition of VOC in the drying process (Ormeci 2008).

**Fate of main ingredients in sludge after drying**

**Variation of main ingredients in sludge after drying**

The volatile composition in GBPS was 65.79%, which slightly exceeded that in XHPS (61.77%). COD in GBPS

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**Figure 5** | The species proportion of VOC: (a) drying at 100 °C; (b) drying at 150 °C.

**Figure 6** | Influence of sludge from different WWTPs on odor concentration and VOC emission.
and XHPS was 155.52 mg/g and 107.06 mg/g, respectively. One quarter of the wastewater treated in XHP was industrial wastewater, which might lead to the difference in volatile composition and COD between the two sludge samples. The pH values in the two sludge samples were almost neutral.

As a by-product of wastewater treatment, dewatered sludge contains not only inorganic particles, colloid, and micro-organisms, but also a large amount of organic compounds, such as proteins, lipids, and fibers. In the thermal drying process, the organic compounds in the sludge are heated and broken down because of high temperature. Some odorous containments in the exhaust gas release to the air, which may cause air pollution. The main pollutants were carbon-containing compounds, nitrogen-containing compounds, and SCCs, which were associated with odors and VOC emissions in the drying process (Harrison et al. 2006; Lehtinen & Veijanen 2011). Figure 7 exhibits the proportions of C, N, and S in the GBPS and XHPS before and after drying at 100 °C.

C, N, and S in both GBPS and XHPS were obviously reduced after drying. For GBPS, C, N, and S decreased by 32.06%, 29.50%, and 39.57%, respectively. By contrast, 12.21%, 7.99%, and 19.89% of these elements, respectively, were reduced in XHPS. The carbon-containing compounds, nitrogen-containing compounds, and SCCs that were reduced during the GBPS drying were much more than those in the XHPS drying, which resulted in higher emission level (Figure 5).

TOC is often used to describe the content of organic compounds in sludge. The protein, carbohydrate, and volatile fatty acid account for 75–85% of the TOC, which are the main components of the organic matter in the sludge. Among these components, protein accounts for nearly 50%.

Table 2 | The percent reductions of TOC, protein, and polysaccharide

<table>
<thead>
<tr>
<th>Drying temperature</th>
<th>GBPS</th>
<th>XHPS</th>
<th>GBPS</th>
<th>XHPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOC (%)</td>
<td>5.90</td>
<td>4.74</td>
<td>9.18</td>
<td>8.61</td>
</tr>
<tr>
<td>Protein (%)</td>
<td>10.44</td>
<td>4.5</td>
<td>11.64</td>
<td>5.43</td>
</tr>
<tr>
<td>Polysaccharide (%)</td>
<td>16.84</td>
<td>43.38</td>
<td>38.19</td>
<td>50.12</td>
</tr>
</tbody>
</table>

When the sludge dried at 150 °C, the loss of TOC, protein, and polysaccharide was more than those dried at 100 °C. For both GBPS and XHPS, the decrease of polysaccharide was markedly higher than that of the other compounds in the drying process, suggesting that polysaccharide was easier to break down.

Breaking down of TOC, protein, and polysaccharide contents resulted in release of VOC. Fatty acids, amino acids, and other organic compounds were generated during protein decomposition and then transformed into organic acid, amines, and CO₂ (Anderson et al. 2002). Carbohydrates were degraded into volatile organic acids (Quitain et al. 2002). SCCs in the sludge were heated to decompose into hydrogen sulfide, thioether, and other volatile sulfur compounds, which are possibly associated with odor pollution.

The variation of DOM in the sludge before and after drying was observed by 3D fluorescence spectrometry. Both GBPS and XHPS had four obvious fluorescence peaks: peak a (λ_ex/λ_em = 230/310–220 nm), peak b (λ_ex/λ_em = 270–280/300–310 nm), peak c (λ_ex/λ_em = 220–230/340–360 nm), and peak d (λ_ex/λ_em = 270–280/340–360 nm). Four peaks were associated with the aromatic ring of amino acids, which is a kind of protein in DOM (Figure 8).

The specific peak and intensity in the 3D fluorescence spectra represent the specific type and DOM concentration, respectively (Ma et al. 2014).

After the sludge was dried at 100 °C for 50 minutes, the peak in the spectra remained similar to that of wet sludge, whereas the intensity was changed. These findings indicated that the species of DOM was almost the same, and the concentration decreased after drying.

Obvious variation in the fluorescent group position and fluorescence intensity could be observed after the XHPS was dried at 150 °C for 30 minutes. The fluorescence peak related to protein disappeared, whereas new peaks, namely, peak e (λ_ex/λ_em = 300–330/390–410 nm) and
peak f ($\lambda_{ex}/\lambda_{em} = 220–240/390–410$ nm) emerged. Generally, these two peaks might belong to humic acid (Shi et al. 2014). The fluorescence intensity was significantly reduced after drying, indicating the variation in concentration of the DOM. The DOM contained in the sludge can be more likely degraded at a higher drying temperature.

### Analysis of condensate

The condensate formed during the sludge drying process at 150 °C was analyzed (Table 3).

The results showed that the TOC in the condensate was as high as 2,570 mg/L, indicating that a large amount of the organic compounds and their converted products transferred from sludge to the condensate. Inorganic ions, such as $\text{NH}_4^+$, $\text{NO}_3^-$, $\text{NO}_2^-$, $\text{SO}_4^{2-}$, and $\text{CO}_3^{2-}$, were also found in the condensate. The nitrogen-containing

### Table 3 | The analysis of condensate formed during sludge drying at 150 °C

<table>
<thead>
<tr>
<th>Substances</th>
<th>Concentration (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{NH}_4^+$</td>
<td>571.71</td>
</tr>
<tr>
<td>$\text{NO}_3^-$</td>
<td>29.75</td>
</tr>
<tr>
<td>$\text{NO}_2^-$</td>
<td>13.81</td>
</tr>
<tr>
<td>$\text{SO}_4^{2-}$</td>
<td>45.25</td>
</tr>
<tr>
<td>$\text{CO}_3^{2-}$</td>
<td>132</td>
</tr>
<tr>
<td>TOC</td>
<td>$2.57 \times 10^3$</td>
</tr>
</tbody>
</table>
substances, SCCs, and carbon-containing compounds in the sludge were converted into ammonium salt, nitrate, nitrite, sulfate, and carbonate during the drying process and were transferred into the liquid phase.

According to the analysis of substances in the three phases during the sludge drying, substances in the sludge were heated and decomposed. The products migrated to the air phase, the condensate and also remained in the dried sludge. Their potential migration in the drying process is shown in Figure 9.

CONCLUSIONS

The composition and emission levels of SCCs, amines, and TVOCs changed with processing temperature and sludge sources, and the odor concentration varied accordingly during the sludge drying process. Substances in the wet sludge were heated and decomposed. Products transferred to the gas phases, condensate and dried sludge. The present study provided the data of odors and VOC emissions, particularly at low temperature drying, which should be considered for air pollution.

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