

Study on the Emission Characteristics and Mechanism of Sulfur-Containing Gas During Sludge Pyrolysis at Low Temperatures

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Abstract

In order to explore the influence of the release of sulfur-containing gases in the process of sludge pyrolysis, temperature, time and calcium-based conditioner were selected to conduct low-temperature sludge pyrolysis experiment on sludge, and effective measures to control the release of sulfur-containing gases such as CS₂, H₂S and SO₂ were proposed. The experimental results show that when the temperature is below 200°C, the release of H₂S gas is less than 50 µg/g. The release amounts of C₂S and H₂S within 3min were 20.84µg/g and 339.42µg/g, respectively. Combined with the release characteristics of the three gases, it was concluded that the drying temperature of the sludge was controlled below 250°C and the drying time was controlled within 1 min. The concentration of sulfur-containing gas is 59.81 mg/m³, 94% lower than that of dry pure sludge gas when the addition of calcium base powder is 20% of the original sludge mass fraction. After absorption of calcium base powder, there are almost no organic compounds containing sulfur and sulfur gas. The research results provide a direction for the selection of pyrolysis sludge treatment process, which is beneficial to control the discharge of harmful gases.

Statement Of Novelty

This work focuses on the release characteristics and control measures of sulfur-containing gases in the process of sludge pyrolysis, which is of great significance for practical industrial application and energy saving and environmental protection. The optimum drying parameters were obtained by comparing different drying temperatures and times. The absorption efficiency of sulfur-containing gas can be greatly improved by using industrial Calcium base powder as conditioner, and the inhibition, absorption and adsorption of calcium based powder to reduce the emission of odor gas is further explained. In short, time, temperature and conditioner affect the emission of harmful gases in the process of sludge drying.

1. Introduction

With the acceleration of urbanization, the output of sludge continues to rise and reach 60–90 million tons by 2020 in China [1, 2]. It is crucial to find appropriate ways to reuse these wastes to reduce their impacts on environment. The most common disposal options of sewage sludge are landfill, land diffusion, and incineration [3,4]. As the moisture content of sludge is ~80%, a drying process is required for the harmless reduction and resource treatment of sludge [5, 6]. However, the inevitable odor emissions that are unavoidable during drying may raise concerns about environmental pollution and human health. There are eight kinds of odorous gases that must be strictly controlled and detected in the emission standard for odor (GB 14554-93). Five of them are sulfur-containing compounds, namely, H₂S, CH₃SH, C₂H₆S, CS₂, and C₂H₆S₂. The influence of sulfur on sludge in the treatment and disposal process should not be underestimated, such as the corrosion of infrastructure caused by sulfur gas emission, the speciation regulation of metals (such as Cu, Zn and Ag), and the undesirable gases produced in the biological treatment process [7,8,9]. Therefore, we need to pay attention to the release and control of sulfur gas in sludge pyrolysis.

S in wasted sludge is primarily constituted of S-containing biomolecules (e.g., amino acids with S-containing side chains), inorganic sulfides, and insoluble sulfate [4,10,11,12]. Compared with most biomass, the characteristics of sludge related to thermochemical conversion during pyrolysis are more complex and

different [13]. It is showed [14] that the release of sulfur-containing odor gases from sludge comes from two processes: the first is mainly the inorganic sulfur release process of free sulfur-containing gas molecules from inorganic sulfur, and the second is the decomposition of sulfur-containing organic matter caused by the heating of sludge and the release of organic sulfur, which produces sulfur-containing polluting gases. During pyrolysis, aliphatic-S and sulfonate were preferentially degraded at low temperature (below 350°C) and sulfate was thermochemically reduced at a temperature above 450°C, while metal sulfides (up to 27%) and thiophenes (up to 70%) were increasingly formed [15]. If these sulfur-containing gases are directly discharged without control and treatment, it will cause great harm to human health and life. It is reported that the main sulfur-containing gases released during a sludge drying process were H₂S and SO₂, and they accounted for 82.4% of the total gas released [6]. Two representative organic sulfides—BS and DHS— were selected to conduct pyrolysis experiments of sludge and NaOH at different temperatures[16]. They discussed the organic sulfide model after adding alkali and analyzed its transformation effect. In particular, Someone [17] proposed that CaO could significantly improve the conversion of sludge into coke and combustible gases (especially H₂ and CO) and explained the effect of CaO on sulfur conversion during pyrolysis. It is found that adding CaO to sludge will result in deoxidation reaction, reducing O-containing compounds in organic matter and adsorbing CO₂ from noncondensable gas [18].

Several scholars are currently interested in the release mechanism of sulfur gas produced during a drying process; however, the absorption and inhibition mechanism of sulfur gas release have not been studied in-depth, and there are no effective control methods for the odor gases released in a drying process. This study focuses on the production technology of “Using a cement kiln tail system to atomize and dry sludge—cement rotary kiln to incinerate and dry sludge” (proposed by Powder Engineering Institute of Xi’an University of Architecture and Technology) and explores how different factors influence odor emission. The research results have a new understanding of the release characteristics of sulfur-containing gas in the process of sludge low-temperature pyrolysis, and the measures to control the emission of sulfur-containing gas have been proposed.

2. Experimental

2.1. Experimental materials and properties

Table 1.1 shows the elemental composition of the sludge[1] and Table 1.2 shows the chemical composition of calcium-based powder[2] used in the experiment. CBP is obtained from the flue gas produced by the kiln of a cement plant. The maximum particle size of CBP is 12,00 μm, the average particle size is 3.12 μm, and the particle size of 90% of the powder is less than 6.88 μm.

Table 1.1 Element Composition of Sludge (RS)%

Element	C	H	O	N	S	Si	Ca	Al	Fe	K	Mg
Composition	30.65	6.14	20.13	3.96	1.81	14.45	6.25	5.7	8.84	3.24	2.18

Table 1.2 Chemical Composition of Calcium Based Powder (CBP)%

SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	SO ₃	Loss	Sum
13.87	2.52	1.74	42.56	2.18	0.68	0.06	0.48	35.02	99.11

2.2. Experimental instruments and methods

The experimental system shown in Fig.1(a) was used to study the effect of sludge temperature and time on the release of sulfur gas. N₂ is used as a carrier for gas transport gas. After the sludge is dried, the content of CS₂, H₂S, and SO₂ in the absorption solution is measured by a spectrophotometer method, and the total amount of each gas released by the quantitative sludge is calculated. The experimental schemes of temperature and time are as follows:

1. Temperature effect experiment: 0.5 g of sludge was put into a 250 ml three-port flask, and the temperature of the heating jacket was controlled at 150°C, 200°C, 250°C, 300°C, and 350°C, respectively, for 10 min.
2. Time effect experiment: 0.5 g sludge was put into a 250 ml three-port flask, the temperature of the heating jacket was adjusted to 250°C, and the heating time was 0.5, 1, 1.5, 2, 3, 4, 5, and 10 min, respectively.

The influence of calcium-based ultrafine powder on sulfur-containing gas is shown in the sludge drying experimental system in Fig 1(b). CVT-1600PC sintering analyzer is the main equipment used to test and record the change of sludge quality during the drying process. The system temperature is controlled by the control system operated by the PC. The dried gas is collected and stored in a gas sampling bag for detecting gas concentration, except for NH₃. Specific experimental steps are as follows:

The material RS and CBP were mixed in order of 0, 20:1, 10:1, and 5:1 and then put into the sintering analyzer for testing. At a room temperature of 20.8°C, the air in the furnace is pumped to 0.06 MPa using a vacuum system and then heated to 200°C and 250°C at a heating rate of 5°C/min for 60 min. The high-temperature mixed gas is transferred through the upper exhaust valve of the sintering analyzer and collected after cooling and drying. The concentration of H₂S gas is determined using gas chromatography. Additionally, the gas released from pure sludge heated and dried at 300°C was collected and adsorbed using CBP. The concentration of H₂S gas was determined and the change of raw material quality was recorded.

3. Results And Discussion

3.1. Effect of temperature on odor emission

As shown in Fig. 2, the release characteristics of main sulfur-containing odors CS₂, H₂S, and SO₂ with drying temperature were measured via the spectrophotometer method.

It shows that although the release of CS₂ is not large during the drying process, the growth rate with increasing temperature is large because CS₂ is produced by the reaction of CH₄ and FeS and the reaction rate increases with increasing temperature; however, the peak temperature of CS₂ formation is 500°C. In the temperature

range of 150°C–350°C and 10 min, the release of CS₂ increased from 17 to 27.2 µg/g, which is an increase of 62.5%. When the temperature is lower than 200°C, the release amount of H₂S gas released is less than 50 µg/g, whereas when the temperature is higher than 200°C, the release amount of the gas released rapidly increases sharply, reaching 386.25 µg/g at 250°C. This is because of the large amount of organic acids produced in this temperature range, which transforms inorganic sulfides into H₂S or decomposes a large amount of organic sulfides[19]. When the temperature rises above 250°C, the growth of H₂S becomes more gradual and, eventually, constant. According to the influence of drying temperatures on SO₂ emission, when the temperature is less than 250°C, SO₂ release is slow and less intense. When the temperature reaches 300°C, SO₂ emission increases from 88.74 to 307.81 µg/g, an increase of ~300%. This is because a large amount of SO₂ is produced by the decomposition of sulfur-containing aliphatic compounds at 300°C, and then, with the increase in temperature, the release amount of SO₂ increases growth is extremely slow.

To conclude, controlling the drying temperature of sludge should be controlled below 250°C reduces the release of the three gases is less.

3.2. Effect of time on odor emission

It can be seen from Fig. 3 that the release characteristics of the main sulfur gases CS₂, H₂S, and SO₂ with drying time were measured via the spectrophotometer method. The figure shows that as time passes, the amount of the three gases released increases continuously, with the gas release amount of gas released increasing significantly at 30 s and tending to be constant at 10 min, and there is no gas was released afterward. This is due to heat transfer between the materials as the sludge is stacked in the three beakers. It takes a certain amount of time to heat the sludge to be heated from room temperature to 250°C. The sludge release rate is low during this time. When the sludge temperature reaches 250°C, the gas release rate increases continuously, releasing a large amount of gas. Fig. 3 shows that the release of CS₂ and H₂S is mainly concentrated in the first 3 min, with the release of C₂S and H₂S being 20.84 and 339.42 µg/g, respectively, accounting for 93.2% and 93.4% of the total release. At this temperature for CS₂, most CH₄ produced by sludge pyrolysis reacts with FeS within 3 min and is consumed completely. For H₂S, this is mainly due to the complete decomposition of most sulfur-containing organic acids. When the time is 2 min, the SO₂ release amount of SO₂ released can reach 77.58 µg/g, accounting for 92.4% of the total release, and then, the release rate rapidly decreases. This is because the sulfur-containing aliphatic group that can be decomposed in the sludge decomposes almost completely in 2 min at a temperature of 250°C.

3.3. CBP inhibits the release of sulfur gas

Fig. 4 shows the variation of H₂S concentration during sludge drying with different CBP contents. The concentration of H₂S in the waste gas decreases significantly as CBP content increases. The concentration of H₂S increases with increasing temperature. The concentration of H₂S in the gas produced by the drying of pure sludge is 1038.62 mg/m³ at a temperature of 250°C. When 10 wt% CBP was added, the concentration of H₂S was reduced by 85%; when the mass ratio of CBP to sludge was 1:5, the concentration of H₂S was only 59.81 mg/m³, which was 94% lower than that of dry sludge gas (1038.62 mg/m³) without CBP. Additionally, the mixed CBP and pH value of sludge were determined. When the amount of CBP was 10 wt% (CBP:sludge =

1:10), the pH value of sludge increased from 6.5 to 11.1, whereas the concentration of H₂S in the tail gas decreased significantly. The concentration of H₂S was 50.57 mg/m³ when dried at 200°C.

Previous studies have shown that heat decomposed aliphatic sulfur and aromatic sulfur in sludge, and then, C–S bonds were broken, producing sulfur-containing gas [20]. Additionally, alkali can inhibit the release of sulfur-containing gas during sludge drying, and the stronger the alkalinity, the better the effect [16,21]. This is because, at a certain temperature, alkali can promote the oxidation of aliphatic sulfur and aromatic sulfur to sulfoxide and sulfone in sludge, respectively, and eventually sulfonic acid may be produced [6,22]. Moreover, sulfoxide and sulfone almost do not produce sulfur-containing gas during the drying process, and their properties are more stable. Fig. 5 shows that R–S–R uniformly represents aliphatic sulfur and aromatic sulfur. Sulfoxide, sulfone, and sulfonate can be labeled as R–SO–R, R–SO₂–R, and R–SO₃–R, respectively. Because of the low bond dissociation energy of the C–S bond in R–S–R compounds, the C–S bond is easy to cleave at low temperatures to form sh-radical and then form H₂S. Following the addition of alkali, a series of reactions, as shown in Fig. 5, occur because of the action of OH⁻. Finally, hexavalent sulfur sulfonic acids are formed through nucleophilic addition, which greatly inhibits the release of H₂S and other gases. Some scholars have proposed that the active components of the conditioner added in the sludge can react with some free groups in the sludge to form precipitation, so that most of the sulfur elements are fixed in various solid compounds, and the relative ratio of sulfates and inorganic sulfides is rapidly increased sharply [23]. Thus, the addition of CaO can cause a series of complex physical and chemical reactions of sulfur-containing substances in sludge, forming chelates with high stability and nonpolar calcium salts.

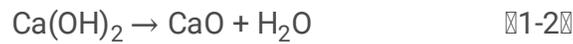
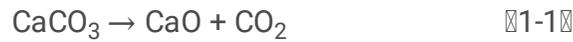
Additionally, alkalinity inhibits the growth of sulfate-reducing bacteria (SRB). SRB are anaerobic bacteria that can reduce elemental sulfur or sulfate to H₂S and other sulfur-containing gases. Thus, SRB activity is crucial for sulfate, sulfite, and organic sulfide in sludge to produce sulfur-containing gas [24]. It is found [25] that the optimal PH value for SRB growth is 7.0. Hence, the release of H₂S and SO₂ can be inhibited by controlling the pH value of the sludge drying process and inhibiting the growth of SRB. To conclude, the addition of calcium-based ultrafine powders, on one hand, uses the strong oxidizing hydroxyl group to change the proportion of all types of organic sulfur in the sludge; on the other hand, it provides an alkaline environment and changes its internal biochemical conditions, thereby inhibiting the release of sulfur-containing gases.

3.4. Absorption and adsorption of sulfur-containing gas by CBP

Some characteristic gases collected in the airbag are shown in Tables 2 and 3. Tables 2 and 3 show that a large number of alkanes, alkenes, alkynes, CH compounds, alkanes, and alkanols are produced when the sludge is decomposed at 300°C. According to the chemical composition of gases in Table 2, the sludge is decomposed without any treatment to produce various amino acids, organic compounds containing nitrogen and sulfur, and various sulfur-containing gases, such as H₂S, CS₂, and COS. Comparing the gas composition in Table 3, there are almost no sulfur-containing organic compounds and sulfur-containing gases. After CBP adsorption, the types of gas collected in the airbag did not significantly change much, but the substances containing S and N in Table 3 were reduced compared with those in Table 2, indicating that the adsorption of sulfur-containing gas in sludge using calcium-based ultrafine powder was very obvious, which helped control the emission of odor gas. The odor of sludge particles is obvious, but when the particles are completely coated

by CBP, the odor is hardly emitted. This is because the odor is covered by a large amount of powder on the surface of the sludge particles, preventing it from passing through the surface fly ash layer.

Calcium-based desulfurizers commonly used in the market now include CaO, Ca (OH)₂, and CaCO₃ [26], and the main component of CBP is CaCO₃. CaCO₃ can produce CaO particles with high specific surface area and high porosity during calcination, which can absorb sulfur gases such as H₂S and SO₂. Second, CaO reacts with SO₂ to form CaSO₄ to realize desulfurization and sulfur fixation . The chemical reactions that occur are as follows:



Because of the evaporation of aliphatic compounds in the process of sludge drying at 200°C–450°C, water in the sludge drying process is not easily lost. The produced H₂S can be partially ionized in the presence of water, and H⁺ and HS⁻ can be generated by one-step ionization, and a small amount of HS⁻ can be ionized in two steps to form S²⁻; with CaO, the amount of H₂S can be ionized to form S²⁻, and by increasing its content, it reacts with water to release heat and form Ca (OH)₂. The alkalinity in the system increases gradually, neutralizing more H⁺, thus promoting the ionization of H₂S and producing more S²⁻, which can react with CaO to produce CaS or react with hydrated Ca(OH)₂ to form CaS; SO₂ produced from organic sulfur decomposition will also react with Ca(OH)₂ to form CaSO₃, and CaSO₄ is more stable under oxidation conditions [27]. Other experimental results [6] also showed that when the sludge was dewatered with CaO as a conditioning agent, alkaline CaO promoted the conversion of most H₂S and SO₂ to CaS and CaSO₄, resulting in a rapid increase in the relative ratio of sulfate to inorganic sulfide. In particular, the addition of CBP, on one hand, produces sludge in an alkaline environment, and the acid-free H₂S and SO₂ molecules can react with CaO and Ca(OH)₂ to form stable calcium salt, thus reducing the inorganic sulfur release process in the subsequent drying process; on the other hand, the alkaline calcium materials can absorb the release of sulfur-containing organic matter during the sludge drying process. Acid gases such as H₂S and SO₂ can further reduce the sulfur released during the drying process.

Generally, the chemical process of absorption must be accompanied by the adsorption process. Calcium-based superfine powder can absorb and adsorb sulfur-containing gas at the same time. The main components of CBP powder are SiO₂ and CaCO₃, and it also contains a lot of amorphous SiO₂ and Al₂O₃, which can be regarded as a type of pozzolanic ash. In the presence of water at normal temperature, properly crushed pozzolan can react with an alkali metal and alkaline earth metal hydrate.

These newly formed hydrated aluminosilicates are usually incomplete crystals, mostly fibrous, with large specific surface area and high-water holding capacity [28]. The results show that the reaction of (2-1)–(2-4) changes the surface structure of the powder, increases the specific surface area, improves the pore structure, and improves the pore structure and the gas adsorption effect, whereas the high-water holding capacity increases the humidity of the powder particles and accelerates the reaction on the surface [29]. CBP powder may also play a catalytic role, especially the high content of silicon, iron, magnesium, and aluminum, and some trace elements can also promote the absorption of gas [30]. Additionally, a large number of studies have shown that the potentially active powder and CaO can be digested to form calcium silicate hydrates and form loose porous structure, thus greatly improving the adsorption of sulfur-containing gas.

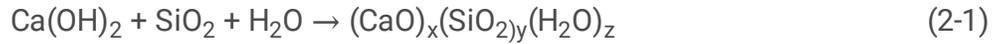


Table 2. Representative gas released by sludge at 300°C

Number	Type	Appearance time (min)	Name	Chemical formula	Molecular weight
1	Hydrocarbon organic matter	0.392	Ketene	C ₂ H ₂ O	42.011
		0.815	Oxalic acid	C ₂ H ₂ O ₄	89.995
		2.258	Methanol-D4	CD ₄ O	36.051
		11.729	(R,R)-Tartaric acid	C ₄ H ₆ O ₆	150.016
		11.729	Butanedioic acid, 2,3-dihydroxy-, [S-(R*,R*)]-	C ₄ H ₆ O ₆	150.016
2	Nitrogenous compounds	0.620	Diazirine	CH ₂ N ₂	42.022
		0.620	Pyrazine, methoxy-, 1-oxide	C ₅ H ₆ N ₂ O ₂	126.043
		0.815	Dimethylamine	C ₂ H ₇ N	45.058
		0.815	Epinephrine	C ₉ H ₁₃ NO ₃	183.09
		0.815	2-Hexanamine, 4-methyl-	C ₇ H ₁₇ N	115.136
		0.815	2-Propanamine, 1-methoxy-	C ₄ H ₁₁ NO	89.084
		3.798	2-Amino-1,3-propanediol	C ₃ H ₉ NO ₂	91.063
		6.214	Methyl isocyanide	C ₂ H ₃ N	41.027
		10.133	Butane, 1-isocyano-	C ₅ H ₉ N	83.073
3	Sulfur-containing substances	0.620	2-Pyrrolidinethione	C ₄ H ₇ NS	101.03
		2.258	Hydrogen sulfide	H ₂ S	33.988
		3.798	Carbonyl sulfide	COS	59.967
		3.798	Ethanone, 1-(5-methylfurfuryl)-, Thiosemicarbazone	C ₈ H ₁₁ N ₃ OS	197.062
		11.729	Carbon disulfide	CS ₂	42.011
		11.729	4,4'-Diisothiocyanatostilbene-2,2'-disulfonic acid	C ₁₆ H ₁₀ N ₂ O ₆ S ₄	453.942
		11.729	Thiourea	CH ₄ N ₂ S	76.01
		11.729	Monoethyl carbonotrithioate	C ₃ H ₆ S ₃	137.963

11.729	Mono-sec-butyl carbonotrithioate	$C_5H_{10}S_3$	165.994
11.729	Mecysteine	$C_4H_{10}ClNO_2S$	151.979
22.729	Monoisopropyl carbonotrithioate	$C_4H_8S_3$	151.979

Table 3. Representative gas components collected by sludge 300°C heating sampling bag

Number	Type	Appearance time (min)	Name	Chemical formula	Molecular weight
1	Hydrocarbon organic matter	22.153	Cyclobutanol	C ₄ H ₈ O	72.058
		22.379	Phthalan	C ₈ H ₈ O	120.058
			Benzene, (butoxymethyl)-	C ₁₁ H ₁₆ O	164.12
2	Nitrogen oxide organic matter	22.379	2-Propanamine, 1-methoxy-	C ₄ H ₁₁ NO	89.084
		22.153	l-Guanidinosuccinimide	C ₅ H ₇ N ₃ O ₂	141.054
			l-Alanyl-l-alanyl-l-alanine methyl ester	C ₁₀ H ₁₉ N ₃ O ₄	245.138
			dl-Alanine ethyl ester	C ₅ H ₁₁ NO ₂	117.079
			Acetic acid, hydroxy[(1-oxo-2-propenyl) amino]-	C ₅ H ₇ NO ₄	145.038
			L-Alanine, methyl ester	C ₄ H ₉ NO ₂	103.063
			Cathinone	C ₉ H ₁₁ NO	149.084
			Benzenemethanol, 3-hydroxy-.alpha.-(methylamino) methyl]-, (R)-	C ₉ H ₁₃ NO ₂	167.095
3	Nitrogenous compounds	22.153	n-Hexylmethylamine	C ₇ H ₁₇ N	115.136
			Amphetamine-3-methyl	C ₁₀ H ₁₅ N	149.12
			N-Dodecylmethylamine	C ₁₃ H ₂₉ N	199.23
			2-Heptanamine, 5-methyl-	C ₈ H ₁₉ N	129.152
			1-Octadecanamine, N-methyl-	C ₁₉ H ₄₁ N	283.324
		22.397	1-Propanamine, N,2-dimethyl-	C ₅ H ₁₃ N	87.105
			sec-Butylamine	C ₄ H ₁₁ N	73.089
			Benzeneethanamine, N-methyl-	C ₉ H ₁₃ N	135.105

4. Conclusion

Experimental results showed that as the sludge drying temperature increased, more CS₂, H₂S, and SO₂ were released from the sludge, and the release of H₂S and SO₂ rapidly increased at 200°C and 250°C, respectively,

indicating that the amount of gas released could be effectively reduced when the temperature was controlled below 250°C. By increasing the sludge drying time, the amount of CS₂, H₂S, and SO₂ released from the sludge increased continuously, and the gas release rate increased first and then decreased. The amount of gas released began to increase significantly at 30 s, and a large amount of gas was released within 3 min, indicating that reducing the drying time can effectively decrease the amount of gas released.

Furthermore, the experimental results show that when the amount of calcium-based ultrafine powder added reached 20% of the original sludge mass fraction, the concentration of sulfur gas released was only 59.81 mg/m³, which was 94% lower than that of the dry sludge gas without CBP. This is because the CBP provides an alkaline environment, which promotes the conversion of more organic compounds in the sludge into more stable sulfoxides and sulfonates, and inhibits the growth of sulfuric acid-reducing bacteria, thereby inhibiting the release of H₂S and SO₂. Additionally, the experiment showed that after adding CBP, the number and damage degree of harmful gases in the sludge drying process decreased. H₂S and SO₂ molecules are neutralized by calcium-based ultrafine powder, forming stable calcium salts. Hence, using CBP and sludge to form a coating ball to inhibit and absorb the sludge dry sulfur odor is an effective way to control the emission of odor gases.

Declarations

Acknowledgments

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Data availability statements

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

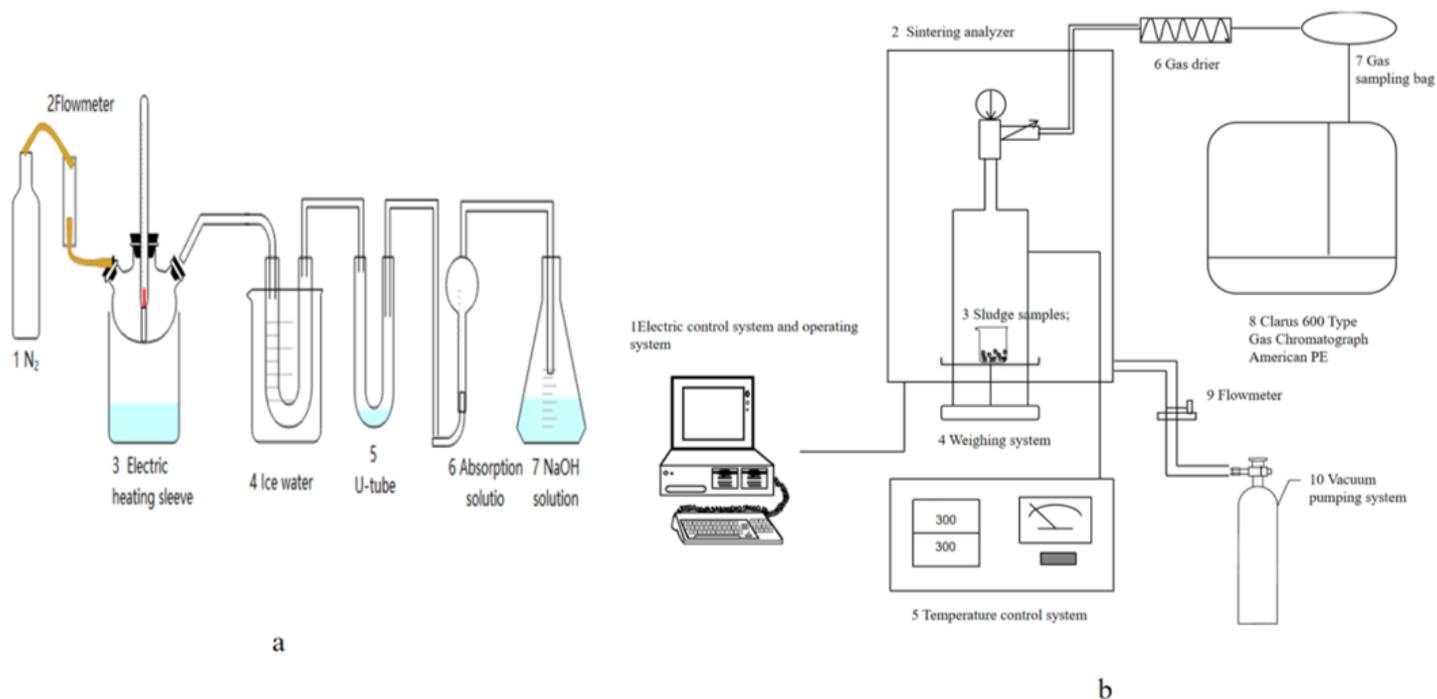


Figure 1

(a) Gas absorption experiment device; (b) Experimental diagram of drying sludge system

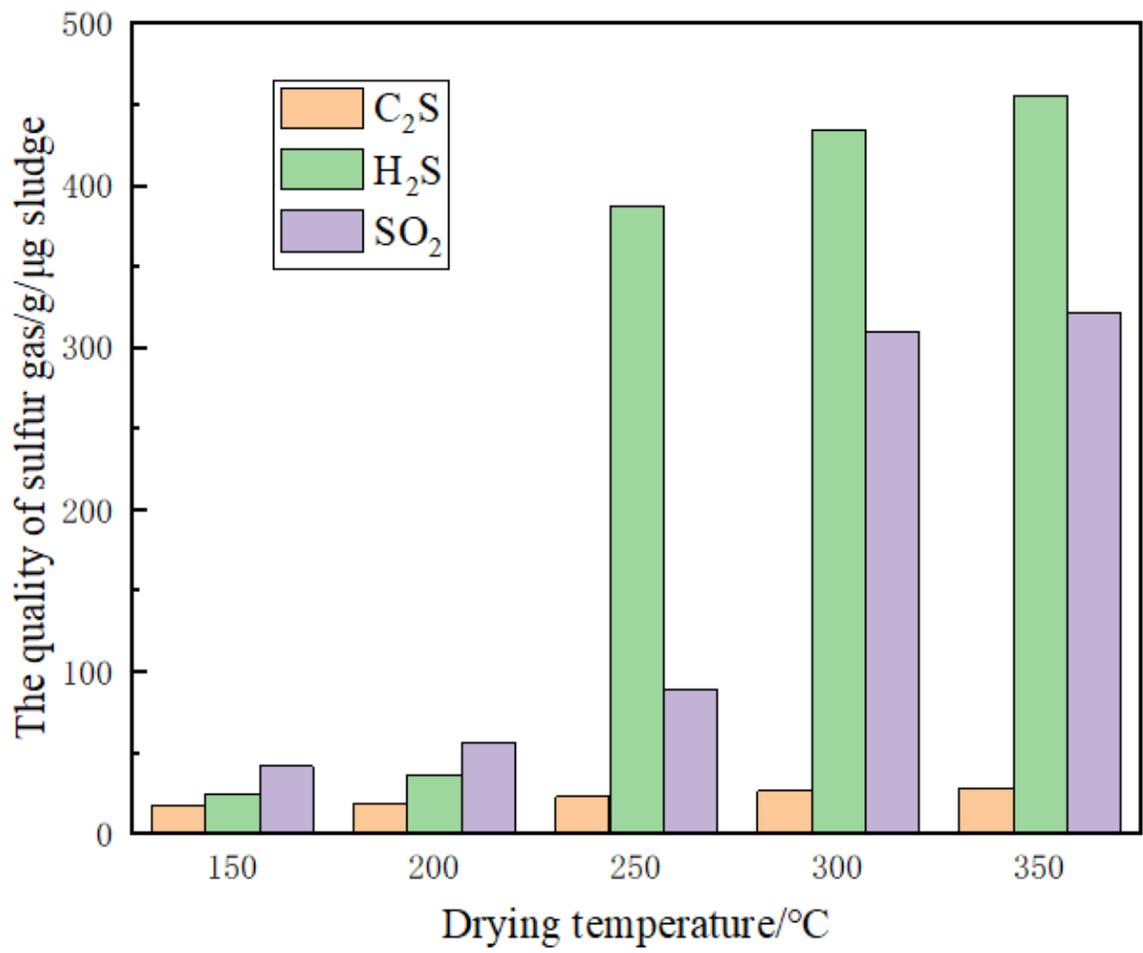


Figure 2

Influence of drying temperature on the amount of release of the gas released

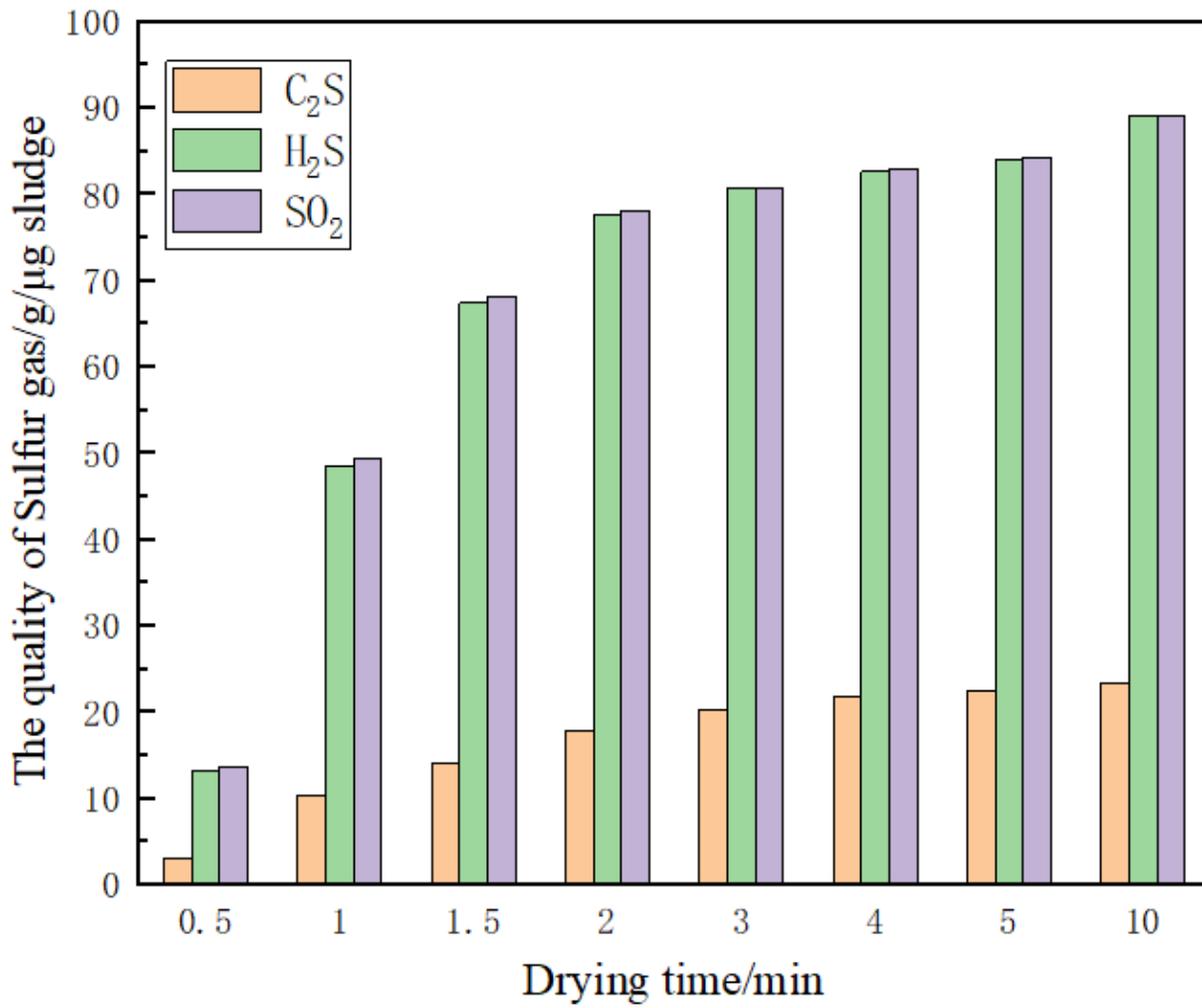


Figure 3

Influence of drying time on the amount of release of the gas released

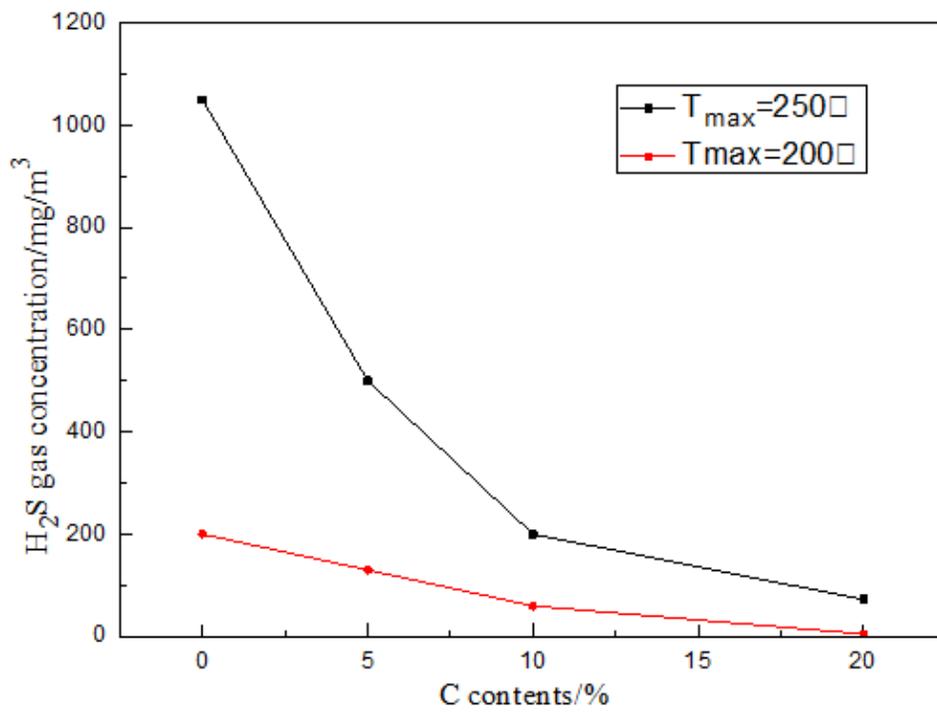


Figure 4

variation of H₂S concentration in sludge drying process with different CBP content

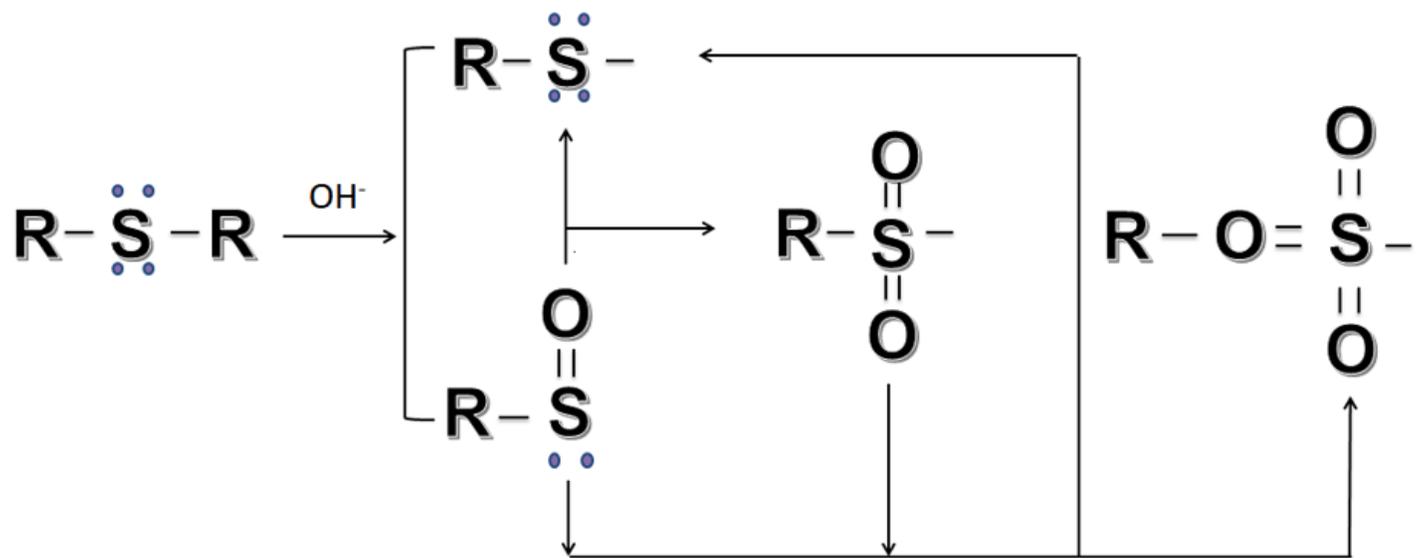


Figure 5

Diagram of organic matter transformation

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