



Utilization of Alum Sludge from Water Treatment Plant as an Adsorbent for Hydrogen Sulfide Removal

Lam Pham Thanh Hien^{1,2}, Le Nguyen Dang Khoa^{1,2}, Dang Van Thanh³, Nguyen Thi Hieu^{1,2}, Tran Thi Phi Oanh^{1,2}, Vo Thi Thanh Thuy^{1,2}, Nguyen Nhat Huy^{1,2,*}

¹Faculty of Environment and Natural Resources, Ho Chi Minh City University of Technology (HCMUT), Ho Chi Minh City, 700000 Vietnam

²Vietnam National University Ho Chi Minh City, Linh Trung Ward, Thu Duc City, Ho Chi Minh City, 700000 Vietnam

³Faculty of Basic Sciences, TNU-University of Medicine and Pharmacy, 284 Luong Ngoc Quyen Rd., Thai Nguyen City, 700000 Vietnam

*Corresponding Author: nnhuy@hcmut.edu.vn

Received: 17 March 2021; Revised: 29 June 2021; Accepted: 30 June 2021; Available online: 1 September 2021

Abstract

Utilizing waste is one of the research directions that receive a lot of attention, especially in the field of the environment. In this study, the H₂S adsorption capacity of modified sludge from Tan Hiep Water Treatment Plant (Ho Chi Minh City, Vietnam) was investigated. Scanning electron microscopy, energy-dispersive X-ray spectroscopy, and X-ray diffraction were used to analyze material properties. The effects of operating conditions such as H₂S concentration and airflow rate were also surveyed. The analysis show the Tan Hiep Water Treatment Plant sludge contains metallic elements that are mainly aluminum. The appropriate temperature for calcining the raw sludge was 300 °C, and the Langmuir isotherm equation is suitable to describe H₂S adsorption process in the concentration range of 50 – 400 ppm with R² = 0.99. Under the optimal operating conditions (e.g., H₂S concentration of 200 ppm and flowrate of 1 L min⁻¹), the adsorption capacity of the alum sludge heated at 300 °C reached 36.65 mgH₂S g⁻¹, which is potential for practical H₂S adsorption in biogas.

Keywords: Adsorption; Alum sludge; Hydrogen sulfide; Water treatment plant sludge

©2021 Sakon Nakhon Rajabhat University reserved

1. Introduction

Hydrogen sulfide (H₂S) pollution is a problem that has been mentioned in many studies. H₂S is a toxic gas, colorless, fetid (i.e., rotten egg smell), heavier than air, originated from both natural and anthropogenic activities, which causes corrosion of pipelines both in gaseous form and in solution and greatly affects the air environment. The source of H₂S is mainly from chemical industries like compost manufacture, crude oil refining, natural gas, and odor generation processes. In fact, there have been many accidents related to H₂S caused by asphyxiation in underground mining and biogas tanks. In biogas tanks, biogas is produced when organic substances degrade under anaerobic conditions. The main components of biogas are CH₄, CO₂, H₂O and other gases such as H₂S, O₂, H₂ and NH₃. Although it accounts for a small amount, H₂S makes the biogas smell unpleasant, along with other gases causing serious health effects, especially the respiratory system.

There have been a lot of studies on the H₂S treatment method and adsorption is one of the most common and effective ways. The adsorption method can be conducted at high concentrations with moderate equipment size, simple equipment, and an easy-to-operate system. Different adsorbents have been examined for their ability to remove H₂S such as activated carbon, zeolite, or metal oxides.

Recently, the application of metal oxides as H₂S adsorbent has been particularly concerned. In addition to their good adsorption capacity, the metal oxides also have a high denaturation ability by changing the synthesis conditions. Metal oxides can be synthesized directly or recovered from wastes (e.g., coffee waste biochar, fly ash, iron sponge, red mud, precipitated calcium carbonate, sewage sludge, drinking water sludge). The reuse of waste containing metal oxides as adsorbents and recovery of sulfur after the treatment process is a promising direction of research. According to Georgiadis *et al.* [1], zinc oxide and Cu/Zn/O composite materials were widely studied by their ability to improve H₂S filtration efficiency but the conclusions about the sulfurization mechanism were still left behind. The H₂S adsorption capacity of ZnO nanoparticles synthesized by ultrasonic vibration assisted precipitation method reached 29.51 mgH₂S g⁻¹ in the study of Nguyen *et al.* [2] which was higher than that of ZnO prepared without ultrasonic. In another work, the red mud (from alum production) heated at 800 °C with 1.50 M of H₂SO₄ solution had a 29.38 mgH₂S g⁻¹ of adsorption capacity [3]. The report of Wu *et al.* [4] shows that fly ash reached 10.40 mgH₂S g⁻¹ of adsorption capacity in the experiment with biogas. The sewage sludge in the study of Ortiz *et al.* [5] also had an H₂S adsorption ability due to its main elements of Fe, Al, Ca and Mg. In Vietnam, water treatment processes in general and supply water treatment in particular often produce a large amount of sludge (denoted as WTPS). However, many treatment systems are still not paid special attention to sludge treatment generating from the processes above. In general, the residual sludge after water treatment is still open and disposed of on a large scale although their toxic level cannot be taken lightly. This amount of sludge, including hazardous sludge, is a difficult problem for the government in the collection and treatment. However, from a scientific perspective, WTPS can generally be reused in many other fields. With the main components of metal oxides, WTPS is expected to be a precursor for the synthesis of selective adsorbents. WTPS in different plants has different compositions so their reusability is also not the same. To our knowledge, the utilization of WTPS-based H₂S adsorbents had only been reported in Polruang's study [6]. Accordingly, WTPS soaked in 2.50 M NaOH solution without washing by DI water can reach H₂S adsorption capacity up to 87.94 mgH₂S g⁻¹ [6]. The use of WTPS both saves a large amount of budget for sludge treatment while also makes sense of using waste to treat other wastes with very high economic value. However, the use of WTPS heated at low temperatures without chemicals (e.g., acids, bases, or salts) has not been reported.

In this study, WTPS was utilized as an adsorbent to treat hydrogen sulfide gas. The effects of modification temperature on the WTPS characteristics and H₂S removal efficiency were investigated. In addition, the change of H₂S performance at different operating conditions was also recorded. The isotherm equations were used to describe H₂S adsorption then the most suitable equation was chosen to calculate kinetic parameters.

2. Materials and Methods

H₂S gas in the experiments was generated from a chemical reaction between the solution of 10% H₂SO₄ and Na₂S.9H₂O solid dissolved in water [2]. The chemicals used are sourced from China with high purity. The raw alum sludge was taken from the Tan Hiep Water Supply Treatment Plant in Hoc Mon District, Ho Chi Minh City, Vietnam. Raw alum sludge was ground and sieved to get the granular size of 0.075 – 0.15 mm before drying at 105 °C for 24 h. The materials were then heated at different temperatures (i.e., 200, 300, 400, 500, and 600 °C) for 5 h, which were named as TH_{abc}, where abc is the heated temperature. The material characterizations were conducted using X-ray diffraction (XRD, D2 Phaser, Bruker), energy-dispersive X-ray spectroscopy (EDX, JSM-IT200, JEOL), and scanning electron microscopy (SEM, JSM-IT200, JEOL).

The experiments were conducted with the lab-scale diagram H₂S adsorption. The inlet airflow was generated by mixing a concentrated stream of H₂S (Flow 1) and a clean air stream (Flow 2) in the right ratio. Thanks to pump, H₂S from the reaction bottle passed to the stabilizer for a more stable

concentration of Flow 1. At the same time, another pump sucked the clean air through the flowmeter to create Flow 2. Depending on the experiment, the suitable rate of Flow 1 and Flow 2 was chosen by adjusting flowmeters. After mixing and achieving the desired concentration (50 – 400 ppm) and flow rate (1 – 4 L min⁻¹), the gas stream was directed to the adsorption column of material where H₂S gas was being captured by the adsorbent. After that, the gas stream continued flowing through the node. A portion of the air was taken to the impingers, where the sample was taken and analyzed for determining the concentration of H₂S gas. The sampling collecting process was carried out according to Vietnam standard (10 TCN 676-2006 - Ministry of Agriculture and Rural Development) with a sample flow rate of 400 – 500 mL min⁻¹. Sample output was recorded every 30 min with the sample time depended on the concentration of H₂S, which usually fluctuates within 5 to 30 min.

Fig. 1 shows the graphical for design of experiments in this study. The adsorption isotherm represents the dependence of the adsorbed capacity at a time on the equilibrium concentration or pressure of the material absorbed at that time at a given temperature. For solid adsorbents, when liquids or gases are adsorbates, the adsorption isotherms are described through equations such as Langmuir (Equation 1) and Freundlich (Equation 2). To evaluate whether the adsorption process is suitable for monolayer adsorption according to the description of the Langmuir equation or not, it is necessary to evaluate through the equilibrium parameter R_L (Equation 3). Based on the R_L parameter, the suitability of the Langmuir adsorption model can be evaluated (Table 1).

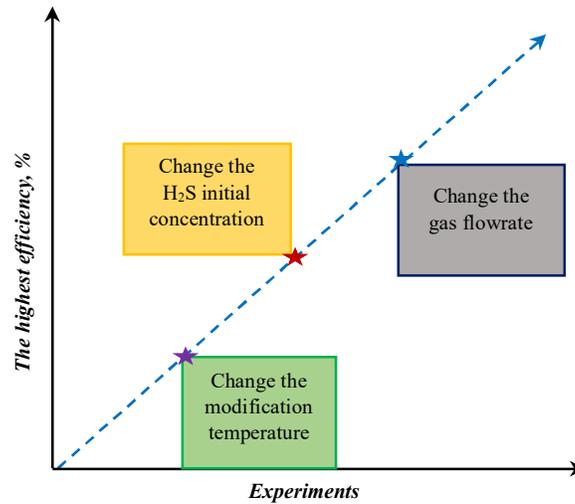


Fig. 1 The graphical for design of experiments.

Table 1 The value of the parameter R_L according to the input concentration [7].

R _L > 1	R _L = 1	0 < R _L < 1	R _L = 0
Not suitable	Linear	Suitable	Not reversible

$$\frac{C_o}{a} = \frac{1}{K_L \times a_{max}} + \frac{1}{a_{max}} \times C_o \tag{1}$$

$$a = K_f \times C_o^n \tag{2}$$

$$R_L = \frac{1}{1 + K_L \times C_o} \quad (3)$$

Where, K_L is the Langmuir equilibrium constant and a is the adsorption capacity (mg g^{-1}). C_o is an inlet concentration (mg m^{-3}). K_F and n are the Freundlich equilibrium constants.

3. Results and Discussion

Material characterizations

SEM images in Fig. 2(a) shows the morphology of the sludge from Tan Hiep WTPS heated at different temperatures. The figures show that the sludge particles are irregularly shaped and heterogeneous due to various particle sizes and shapes. Based on the SEM results, the sludge has compact texture particles with amorphous structure [8]. The XRD patterns in Fig. 2(b) show the similarity of the crystal structure composition of the Tan Hiep Water Treatment Plant Sludge after being heated. Compared to TH105, the heated materials (i.e., TH200, TH300 and TH400) had a slight peak shift to the right while the peak intensity was not significantly different between the samples. Particularly with the sample TH200, peak intensity increased when compared to the dried sludge (TH105), which may be due to the material crystallization at the appropriate temperature of 200 °C. A large of quartz (SiO_2) and kaolinite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$) mineral was found in the structure of Tan Hiep WTPS, similar to study [9]. According to Monteiro *et al.* [10], water treatment sludge contains kaolinite, quartz, gibbsite ($\text{Al}(\text{OH})_3$), and goethite ($\alpha\text{-FeOOH}$), which were the main crystalline phases. The existence of gibbsite and goethite is the basis for the presence of elements such as Al and Fe in EDX patterns of materials (Fig. 3). Through the heat treatment, the chemical reactions that occur include the conversion from hydroxides to metal oxides which have the ability to absorb acid gases [10]. Moreover, the presence of some alkali metal is due to the presence of minerals such as feldspar (e.g., alkali feldspar - KAlSi_3O_8) that was found in the XRD patterns of adsorbents. The EDX patterns of TH300 in Fig. 3 validates that the element composition on the surface of dried sludge (TH105) and heated sludge (TH300) was similar except that the S atom presented in sample TH105 and disappeared after heating. The presence of aluminum and iron (at a lower density than aluminum) in the Tan Hiep WTPS was seen as positive signs for the WTPS-based H_2S adsorbent. The results of sludge composition are similar to the study of Polruang and partners when besides O and Si, Fe and Al were also found in raw drinking water sludge from Banglen Water Treatment Plant in Nakhonpathom, Thailand [6]. This similarity may be due to the similarity in water source properties and treatment technology applied at the water treatment plants. The change in density of elements on the WTPS surface clearly depended on the heating temperature. In the sample TH105, element O content accounted for 53.65% and this percentage increased gradually in the direction of increasing heating temperature (55.30% with sample TH300). The increase of O content in the sludge due to the heat treatment process helps the elements with more valence such as Al and Fe to easily convert to the more stable atom configuration.

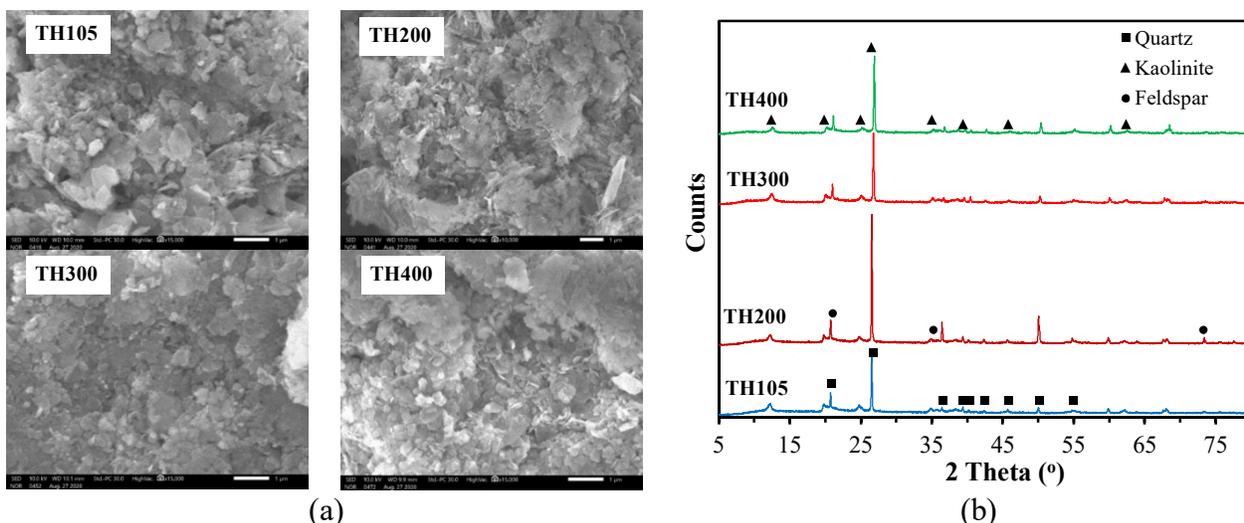


Fig. 2 SEM images (a) and XRD patterns (b) of Tan Hiep Water Treatment Plant Sludge heated at different temperatures.

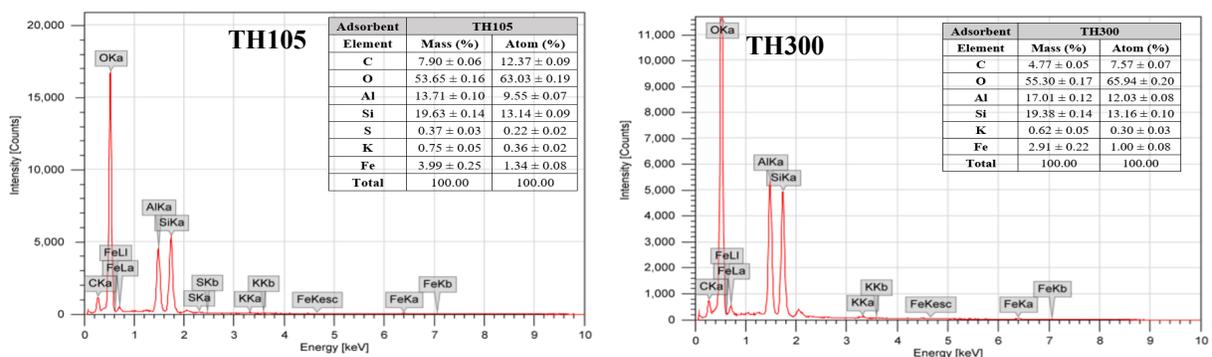


Fig. 3 EDX patterns of Tan Hiep Water Treatment Plant Sludge heated at 105 and 300 °C.

Experiments of H₂S adsorption - Effect of material modification temperature

In this part, H₂S adsorption experiments were conducted with adsorbent materials heated at different temperatures with an inlet concentration of around 100 ppm ± 5%, 3 g of adsorbent amount, and 2.50 L min⁻¹ of flow rate. The results are displayed in Fig. 4(a). With the same amount of material used and the H₂S inlet concentration in each experiment, the H₂S adsorption capacity between the materials had a small difference, ranges from 7.25 mg g⁻¹ to 16.90 mg g⁻¹. However, materials heated at temperatures of 500 and 600 °C (TH500 and TH600) have significantly low adsorption capacities of 9.10 mg g⁻¹ and 7.25 mg g⁻¹, respectively. Other materials had an adsorption capacity of 1.56 to 2.33 times higher than the material with the lowest capacity. In the TH300 sample, the adsorption capacity reached 16.90 mg g⁻¹, which was 2.33 times higher than that of TH600. The saturation time was in the range from 150 min (TH600) to 287 min (TH200). These results showed that the heat treatment at low temperatures improved the ability of the sludge for H₂S adsorption. This can be because the porous structure and the existence of metal oxide phases are favorable conditions for the formation of adsorption centers. With the use of aluminum alum in the Tan Hiep plant for the flocculation, the composition of the heated sludge contains metal oxides and hydroxides such as Al₂O₃, Fe₂O₃ which have the ability to absorb acid gases such as H₂S. At the same time, volatile components and especially water were removed during the heat treatment that can help the increase of porosity and surface area of the material, which improves adsorption efficiency. Specifically, under the influence of temperature through heat treatment, some metal hydroxides have phase transformation such as FeOOH (Geothite) to Fe₂O₃ and Al(OH)₃ to Al₂O₃. Next, the H₂S adsorption process occurs, forming sulfur salt with metal. In addition, O-containing

groups also promote the ability to oxidize H_2S , forming H_2SO_4 on the material surface [11]. When the heating temperature increased, the adsorption capacity of the material decreased. The great change of the sludge structure under high temperature results in a corruption of porous structure and a decrease in the surface area of the sludge material, which makes the H_2S gas molecules inaccessible. This is different from the case of sewage sludge, where the high temperature gasification (700 °C) improved the efficiency of the modified sewage sludge [12, 13]. This difference can be determined by the composition and nature of the raw sludge. Therefore, it is necessary to study the resonance effects of many factors in the material modification process in the future to better understand the effect of temperature as well as other factors in the material preparation process.

Experiments of H_2S adsorption - Effect of H_2S initial concentration

In previous results, the adsorbent TH300 had the highest capacity and was selected to perform the experiments to determine the effects of operational conditions on the H_2S adsorption process. The experiment was conducted at 5 inlet concentrations, ranging from 50, 100, 150, 200 and 400 ppm with a material weight of 3 g and 2.50 L min^{-1} of flowrate. Fig. 4b displays the change of the adsorption capacity of the TH300 material with the increase of H_2S concentration. The results showed that, with the same amount of adsorbent, when the H_2S concentration increased, the capacity also increased gradually. When the concentration of H_2S increased from 50 to 400 ppm, the adsorption capacity increased from 13.42 mg g^{-1} to 25.95 mg g^{-1} . This change can be explained by the concepts of monolayer and multilayer adsorption. Specifically, when the input H_2S concentration is low, at each adsorption position only one H_2S molecule is attached, which is monolayer adsorption. In contrast, when the input concentration is high, each adsorption position of the adsorbent could adsorb more than one molecule, that is multilayer adsorption. The results also showed that when the concentration of input H_2S increased from 50 to 400 ppm, the saturation time of the TH300 sludge sample decreased from 400 min to 148 min. This can be explained that the adsorption centers are covered faster so the adsorption efficiency decreases faster.

To determine the specific parameters for H_2S adsorption, it is necessary to conduct H_2S adsorption experiments at different concentrations. In this research, the experiment was run with 5 different input H_2S concentrations. At each input concentration, the saturation time of the adsorbent was recorded and the adsorption capacity was also determined. From the experimental results, the Langmuir and Freundlich isothermal adsorption equation can be built for the TH300 sludge with the corresponding parameters and the correlation coefficient R^2 of the two equations was compared. The results are summarized and presented in Table 2. To evaluate whether the adsorption process is suitable for monolayer adsorption according to the description of the Langmuir equation or not, it is necessary to evaluate through the equilibrium parameter R_L in Table 2. One can see that the adsorption of H_2S on TH300 material is more suitable with Langmuir ($R_2 = 0.99$) than Freundlich ($R_2 = 0.93$) isotherm adsorption model. R_L values were all less than 1 in the investigated input concentrations, so it is possible to conclude that the isotherm model Langmuir is suitable for H_2S adsorption by TH300 material. H_2S was adsorbed on the TH300 material in addition to physical adsorption due to the electrostatic attraction, but also chemical interactions of aluminum and a small proportion of iron minerals with H_2S . However, the H_2S adsorption by TH300 material was still inclined to physical adsorption, where the adsorption force was weak. The Langmuir adsorption isotherm model was usually applied to the monolayer adsorption process. Accordingly, all the adsorption centers are in equilibrium and the surface is homogeneous. Each molecule is adsorbed only on a specified center and independently adsorbed molecules do not interact with each other. This proves that the adsorption centers on the surface of this material are relatively homogeneous and that the monolayer adsorption phenomenon is more dominant. From the graph, it is possible to calculate the maximum adsorption capacity a_{max} of 30.96 mg g^{-1} .

Table 2 The kinetic parameters and R_L of adsorption by TH300.

Freundlich isotherm			Langmuir isotherm					R_L value				
Kinetic parameters			Kinetic parameters		Kinetic parameters							
n	K_f	R^2	a_{max} (mg g ⁻¹)	K	R^2	C (ppm)	50	100	150	200	400	
0.34	6.83	0.93	30.96	0.10	0.99	R_L	0.13	0.07	0.05	0.04	0.02	

Experiments of H₂S adsorption - Effect of gas flowrate

In this experiment, the gas flow rate was changed from 1 to 4 L min⁻¹ with an inlet concentration of around 100 ppm ± 5% and 3 g of TH300. Fig. 4(c) shows that when the flow rate was greater, the adsorption capacity of the sludge decreased. When the input flow rate was increased from 1 to 4 L min⁻¹, it could be seen that the adsorption capacity decreased from 17.38 to 16.10 mg g⁻¹, and the saturation time decreased by 385 min (from 600 min to 215 min). This can be explained as follows. When the flow rate is smaller, the contact time between the H₂S gas and the adsorbent is larger so that the adsorption capacity could increase and vice versa. The adsorption process under kinetic conditions can be characterized by a kinetic equation, where the adsorption rate or the adsorption capacity is proportional to the dynamics of the adsorption and the mass transfer coefficient (K_y). With a constant inlet concentration, as the input flow increases, the mass transfer coefficient increases. Assuming the isotherm adsorption process by the TH300 material is represented by the Langmuir equation, with parameters of the average diameter of the adsorbent particle, the diffusion coefficient of the adsorbent depends on the process temperature and the dynamic viscosity. As the gas mixture is constant, K_y is a function of the gas flow velocity calculated in the free cross-section of the device. The adsorption process under dynamic conditions can also be concentrated by the retention time of the inlet mixture from the moment it begins flowing to the adsorbent layer until it leaves the adsorbent layer. It is easy to see that the amount of mass transfer is inversely proportional to the flow rate of the airflow into the device. When the flow rate is smaller, the contact time between the gas and the adsorbent is larger, which should increase the adsorption capacity and vice versa.

The break-through curve with H₂S concentration of 200 ppm, adsorbent amount of 3 g, and flowrate of 1 L min⁻¹ using TH300 is shown in Fig. 4(d). It can be seen that the optimal operating conditions help the H₂S adsorption process become significantly more efficient. The saturation time reached 600 min, which was a great improvement. The smaller inlet gas mixture increases the contact time between the H₂S gaseous molecule and the adsorbent surface, resulting in an extended saturation time of the adsorbent. At an inlet concentration of 200 ppm, at each adsorbent position of the adsorbent attach more than one gas molecule, making the adsorption capacity more efficient. Compared with other studies, the H₂S adsorption capacity of TH300 under optimal conditions in this study (36.35 mg g⁻¹) is higher than that of heat and acid-modified red mud (29.38 mg g⁻¹) [3], fly ash (10.40 mg g⁻¹) [4], and sewage sludge (8.63 mg g⁻¹) [5]. However, this value is much lower than the capacity of adsorbent made from sewage sludge (131 mg g⁻¹) [12] and drinking water sludge (87.93 mg g⁻¹) [6], which could be due to the different elemental content of the sludge.

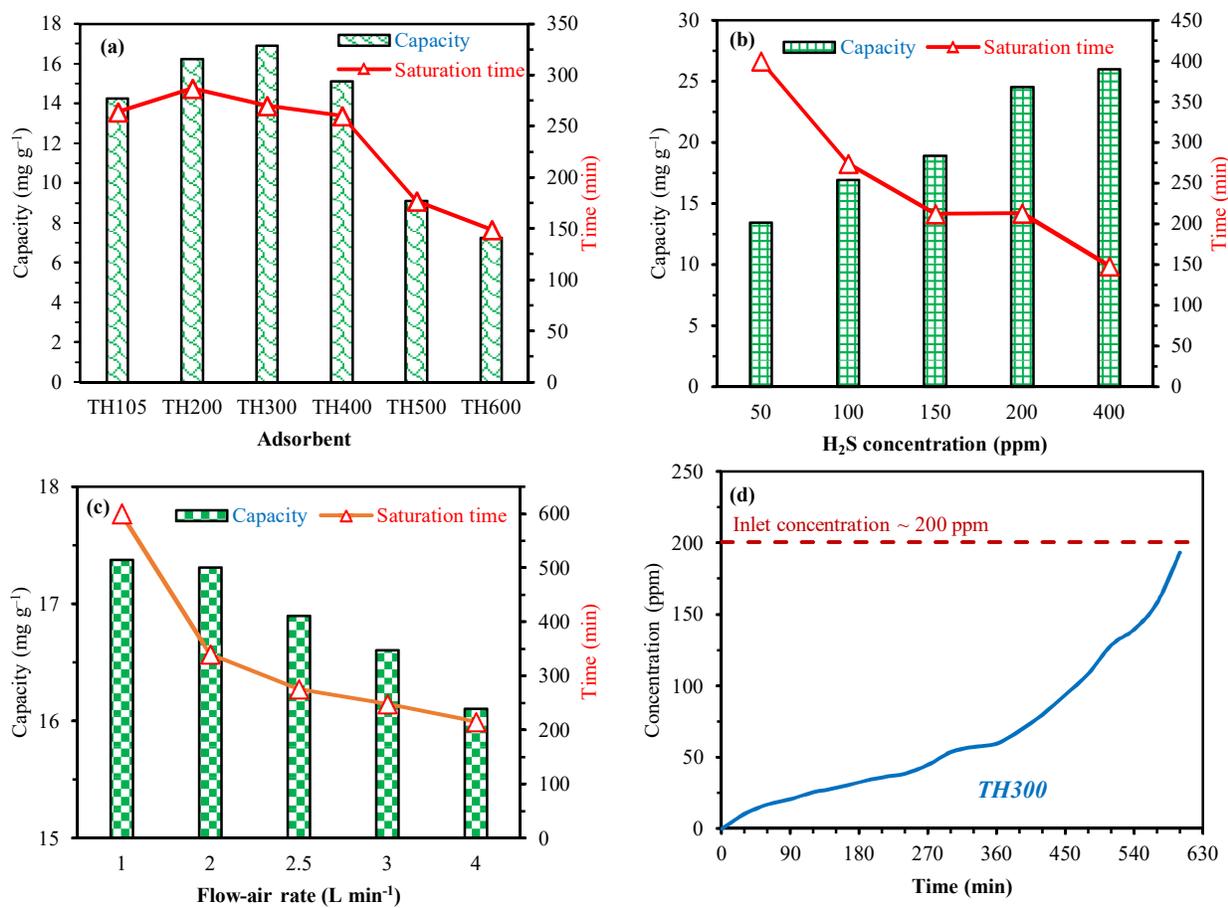


Fig. 4 (a), (b), and (c) H₂S adsorption capacity and saturation time in different adsorbent, H₂S concentration, and flow-air rate, respectively, and (d) H₂S adsorption experiment by TH300 with optimal conditions.

4. Conclusion

This study is an attempt to utilize industrial waste (waste alum sludge from supply water treatment) for the treatment of another waste (hydrogen sulfide in the gas phase). It is to produce a new and efficient adsorbent with an adsorption capacity of 36.35 mg g⁻¹ by an easy-to-find material (alum sludge) and simple fabrication process (heated at 300 °C). The porous structure and metal adsorption centers of material activated at 300 °C are expected to be the cause of the improved processing efficiency of TH300. On the principle of reuse of waste for waste treatment, the conducted study can solve a large amount of untreated waste, used as an adsorbent for waste gas treatment, contributing to reducing emissions into the environment so that it can satisfy the demand of removing hydrogen sulfide and reuse the industrial waste in Vietnam.

5. Suggestions

Beside heat treatment method, impregnation with alkaline or acid solutions and modification of some oxide metals should be applied in order to test the modification of materials which is a very important process and then compare the efficiency with other drinking water plants. Temperature, humidity and actual source of pollution also be considered to make the research more complete and widely applied.

6. Acknowledgement

This research is funded by Ho Chi Minh City University of Technology - VNU-HCM under grant number T-MTTN-2020-58.

7. References

- [1] A.G. Georgiadis, N.D. Charisiou, M.A. Goula, Removal of hydrogen sulfide from various industrial gases: A review of the most promising adsorbing materials, *Catalysts*. 10 (2020) 521.
- [2] N.N. Huy, V.T.T. Thuy, N.H. Thang, N.T. Thuy, T.T. Khoi, D.V. Thanh, Facile one-step synthesis of zinc oxide nanoparticles by ultrasonic-assisted precipitation method and its application for H₂S adsorption in air, *J. Phys. Chem. Solids*. 132 (2019) 99 – 103.
- [3] L.P.T. Hien, L.T.A. Huy, P.D. Thanh, L.N.D. Khoa, B.K. Le, L.T.K. Thi, V.T.T. Thuy, N.N. Huy, Preparation of activated red mud and its application for removal of hydrogen sulfide in air, *Sci. Tech. Dev. J.-Eng. Tech.* 2 (2019) SI40 – SI5.
- [4] H. Wu, Y. Zhu, S. Bian, J.H. Ko, S.F.Y. Li, Q. Xu, H₂S adsorption by municipal solid waste incineration (MSWI) fly ash with heavy metals immobilization, *Chemosphere*. 195 (2018) 40 – 7.
- [5] F.G. Ortiz, P. Aguilera, P. Ollero, Biogas desulfurization by adsorption on thermally treated sewage-sludge, *Sep. Purif. Technol.* 123 (2014) 200 – 13.
- [6] S. Polruang, P. Banjerdikij, S. Sirivittayapakorn, Use of drinking water sludge as adsorbent for H₂S gas removal from biogas, *Environmentasia*. 10 (2017) 73 – 80.
- [7] W.L. McCabe, J.C. Smith, P. Harriott. *Unit Operations of Chemical Engineering*, 7th ed., McGraw-Hill Education, Boston, 2005.
- [8] H.M. Owaid, R. Hamid, M. Taha, Influence of thermally activated alum sludge ash on the engineering properties of multiple-blended binders concretes, *Constr. Build. Mater.* 61 (2014) 216 – 29.
- [9] H. Awab, P.T. Paramalinggam, A.R.M. Yusoff, Characterization of alum sludge for reuse and disposal, *Mal. J. Fund. Appl. Sci.* 8 (2012) 209 – 213.
- [10] S. Monteiro, J. Alexandre, J. Margem, R. Sánchez, C. Vieira, Incorporation of sludge waste from water treatment plant into red ceramic, *Constr. Build. Mater.* 22 (2008) 1281 – 1287.
- [11] T.J. Bandoz, On the adsorption/oxidation of hydrogen sulfide on activated carbons at ambient temperatures, *J. Colloid Interface Sci.* 246 (2002) 1 – 20.
- [12] A. Ros, M.A. Montes-Moran, E. Fuente, D.M. Nevskaja, M.J. Martin, Dried sludges and sludge-based chars for H₂S removal at low temperature: influence of sewage sludge characteristics, *Environ. Sci. Technol.* 40 (2006) 302 – 9.
- [13] X. Xu, X. Cao, L. Zhao, T. Sun, Comparison of sewage sludge-and pig manure-derived biochars for hydrogen sulfide removal, *Chemosphere*. 111 (2014) 296 – 303.