Biodegradation of sulphide in biogas by biofilm on salak fruit seeds: The effect of intra-film-gradient

Retno A. S. Lestari^{1,*}, Wahyudi B. Sediawan², and Sarto²

¹Chemical Engineering Department, 17 Agustus 1945 University, Semarang, Indonesia

²Chemical Engineering Department, Gadjah Mada University, Jl. Grafika 2 Yogyakarta 55281, Indonesia

Abstract. Elimination of H₂S in biogas was performed by bio-filtration, in which H₂S degrading bacteria immobilized on the packing material inside a column. Bacteria was taken from the local area, while salak fruit seed was used as packing material because it has a quite large carbon content, porous and has a high water absorption capability. To obtain a quantitative description of the process, which is useful in the design of large-scale bio-filters, two kinetics models were proposed. Model 1 assumes intra-film gradient does not exist and the gas phase is quasi-steady-state. Model 2 assumes intra-film gradient exists and the gas phase is quasi-steady-state. Comparison of the calculation results using the two models to the experimental data suggested the use of model 2. This conclusion is based on both the trend and the accuracy. The trend of model 1 is more conceivable. However, for rough calculation, model 1 could be used for the reason that it is simpler than model 2. The average absolute errors of model 1 and 2 are comparable, approximately 6 ppm. It can also be concluded that intra-film gradient significantly affects the overall rate processes, while the gas phase can be assumed to be quasi-steady-state.

1 Introduction

One of the potential biomass-based materials for alternative energy is biogas. It is commonly derived from the anaerobic decomposition of organic substances such as animal waste, household waste, agricultural waste, waste water [1]. Biogas is a gas produced by fermentation of organic material by microorganisms in anaerobic condition. This anaerobic process follows the stages of the hydrolysis, asidogenesis and methanogenesis [2]. According to Syed et al. [3], biogas was composed of methane (CH₄) 55-70%, carbon dioxide (CO₂) 30-45% and hydrogen sulphide (H₂S) 0-1.5%. Although the sulphide compounds contained in biogas are relatively small, they can be spoiling and even damage the equipment used on the utilization of biogas because it is corrosive [4].

Hydrogen sulphide removal process in biogas can be performed by physical and chemical processes such as absorption [5, 6] scrubbing [7], adsorption [8] and reactive absorption. Physical and chemical processes are costly and produce other waste.

Another way to remove sulphide compounds in biogas are biochemical conversion with bio-filtration method [9]. This process uses a bio-filter containing sulphide degrading bacteria immobilized on the surface of the packing material [10].

The use of salak fruit seeds for bio-filter media has never been done. Salak fruit seeds (SFS) easily absorb water, have a nearly uniform size, containing nutrition and

are relatively hard. Furthermore their availability were abundant and cheap.

This research aims to eliminate sulphide compound contained in biogas using a bio-filter with SFS as packing material, and sulphide degrading bacteria taken from local area, as well as to get a kinetic model that could be used in designing a large scale system of sulphide elimination in biogas using bio-filter. Special focus in this study concerns with the effect of intra-film-gradient in the biofilm.

Studies on sulphide gas removal with bio-filters have been extensively conducted, but the use of salak fruit seeds as packing material have never be done. Studies on the removal of H₂S in biogas using a bio-filter with other packing materials, mostly focused on semi quantitative descriptive aspects, namely efficiency of removal (RE) of H₂S gas. Although there are researchers who studied quantitative descriptive, their approaches are still open for improvement.

This work is a quantitative descriptive study; the fundamental concepts of mass transfer and kinetics of biochemical reactions of sulphide compounds in the packed bed biogas are explored and laboratory experiments are also conducted to verify the kinetic model proposed.

Bio-filtration process is relatively simple. Gas containing H₂S was flowed through a pile of packing material which has a surface coated by pollutant-degrading bacteria as a biofilm [11]. Hence, sulphide is absorbed by biofilm, and oxidized by microorganism to

* Corresponding author: retnotengaran@gmail.com

be elemental sulphur (if oxygen was limited) and SO_4^{2-} (if oxygen is in excess) [12].

The packing material can be either organic or inorganic compounds. In selecting the support of bio-filter there are several criteria that must be fulfilled include nutrient content (source of C and N), moisture content, pH, porosity, ability to absorb contaminants, lightweight, and cheap [12, 13].

Biofilms are microorganisms that attached and stick together in a polymer matrix [14]. The attachment of microorganisms on the surface of the packing material is very important for the initiation of the development of biofilm [15].

Sulphide-oxidizing bacteria include: bacteria of the genus *Thiobacillus* (kemoautotrof/ litotrof), green and purple sulfur bacteria (photoautotrophs), and types of heterotrophic include *Athrobacter*, *Bacillus*, *Mikrococcus*, *Mycobacterium* and *Pseudomonas* [16].

In this research used biogas, the observation to investigated hydrogen sulphide concentration at some axial position in the column at the various time at 1 phase. At the other paper, the research used the liquid solution of hydrogen sulphide and with difference conditions and difference model. Mathematical model proposed in other paper assumed no intra-film-gradient. [17].

2 Mathematical models

Some previous researchers who have done modelling in the process of gas and liquid waste handling using bio-filters include Spigno et al. [18] in the elimination of phenol, Majumder et al. [19] in the process of removal of divalent copper dissolved in water, Jaber et al. [20] in modelling bio-filters for hydrogen sulphide contained in the air, Meena et al. [21] makes the mathematical modelling of the separation of a mixture of hydrophilic (methanol) and hydrophobic (α Pinene), Santos et al. [22] used a mathematical model for the removal of hydrogen sulphide by oxidation in the bio-filter, Kim and Deshusses [23] calculate the mass transfer coefficient on the packing material used for bio-filter, either in the gas layer or the liquid layer. Furthermore Yang et al. [24] makes modelling of porosity variations of bio-filter equipment used in rotary drum, Ramirez et al. [25] studied the kinetics of microbial growth and biodegradation of methanol and toluene, De Visscher and Li [26] studied the disappearances modelling toluene contained in the air, Agarwal et al. [27] studied the mass balance for phenol degradation events. Modelling in this study was set-up by adopting and combining the basic ideas that emerged in previous studies.

The mathematical modelling of sulphide removal process with bio-filter columns proposed was based on the most fundamental concepts of mass transfer, phase equilibrium and kinetics of chemical reactions, and tried to avoid the use of special empirical equations. The solution of the mathematical equations formed is also based on common numerical methods, and avoiding special simplification. Two models were proposed with the objective to study the effects of intra-film-gradient to the rate of the overall process.

2.1 Model 1

Model 1 by Lestari et al. [28] assumes that biofilms are relatively thin, so there is no concentration gradient in the biofilm. Therefore the concentration of sulphide in the biofilm is uniform and the value is the same as the sulphide concentration at the surface of biofilm ($C_s = C_{si}$). Furthermore, the sulphide concentration in the biogas flowing in the column is considered to be quasi-steady-state.

In the model development, further following simplifications are applied:

1. The gas phase is plug-flow with no axial dispersion.
2. The biofilm is formed on the surface of the SFS only.
3. The thickness of the biofilm is relatively small compared to size of the SFS, so the geometry of the biofilm can be assumed as slab.
4. Biodegradation reaction occurs in the biofilm only, and follows Monod's type equation.
5. The biofilm thickness increases as time progresses.
6. The system is isothermal.

Sulphide material balance in the biofilm produces:

$$\frac{\partial C_s}{\partial t} = \frac{k_c}{\delta} (C_g - C_{gi}) - r_A \quad (1)$$

If the gas-bio-film equilibrium of sulphide follows Henry's type equation, then:

$$C_{gi} = H_s * C_s \quad (2)$$

The rate of biodegradation follows Monod's equation:

$$r_A = \frac{\mu_{\max} C_s}{C_s + K_s} \quad (3)$$

The thickness increase of the biofilm is caused by the increase of the number of microbes, so:

$$\frac{d\delta}{dt} = \frac{Y_x}{S} r_A \cdot \delta \quad (4)$$

The material balance of the sulphide in the gas, assuming quasi-steady-state, gives:

$$\frac{dC_g}{dz} = - \frac{k_c a_s S}{G} (C_g - C_{gi}) \quad (5)$$

The models proposed were solved numerically by finite difference approximation as follows:

$$(C_s)_{j+1} = (C_s)_j + \frac{k_c \Delta t}{\delta} ((C_g)_j - H_s (C_s)_j) - (r_A)_j \quad (6)$$

$$\delta_{j+1} = \delta_j + \frac{AN}{\rho} r_A \delta_j \Delta t \quad (7)$$

$$(C_g)_{i+1,j} = \frac{(C_g)_{i,j} + \gamma \cdot H_s \cdot \Delta z \cdot (C_s)_{i+1,j}}{(1 + \gamma \Delta z)} \quad (8)$$

2.2 Model 2

Model 2 is the improvement of model 1, in which the biofilm is considered relatively thick, so the value of C_s in the biofilm is considered to be not uniform. Meanwhile the sulphide concentration in the biogas flowing in the column is considered to be quasi-steady-state.

The sulphide material balance in the volume element in the biofilm gives:

$$\frac{\partial^2 C_s}{\partial x^2} - \frac{1}{D_e} r_A = \frac{1}{D_e} \frac{\partial C_s}{\partial t} \quad (9)$$

The rate of biodegradation is the same as equation (3) in model 1. The gas-bio-film equilibrium of sulphide follows Henry's type equation as equation (2). The material balance of the sulphide in the gas, assuming quasi-steady-state, is also the same as equation (5).

The thickness increase of the biofilm is caused by the increase of the number of microbes and can be calculated as follows:

$$\int_{\delta_0}^{\delta} d\delta = \frac{Y_x}{\rho} \int_{X=0}^{X=\delta} r_A dx \quad (10)$$

The models proposed were solved numerically by finite difference approximation.

$$(C_G)_{i+1,j} = \frac{(C_G)_{i,j} + \gamma \cdot H_s \cdot \Delta z \cdot (C_s)_{i+1,j}}{(1 + \gamma \Delta z)} \quad (11)$$

$$(C_s)_{i,j+1} = \frac{(C_s)_{i-1,j} + (M-2)(C_s)_{i,j} + (C_s)_{i+1,j}}{M} - \Delta t \cdot (r_A)_{i,j} \quad (12)$$

$$M = \frac{(\Delta X)^2}{D_e (\Delta t)} \dots \dots \dots (i = 2, 3, 4, \dots, N)$$

$$(C_s)_{1,j+1} = (C_s)_{1,j} + \frac{2k_c \Delta t}{\Delta x} ((C_G)_j - H_s (C_s)_{1,j}) - \frac{2De\Delta t}{(\Delta x)^2} ((C_s)_{2,j} - (C_s)_{1,j}) - \Delta t (r_A)_{1,j} \quad (13)$$

$$(C_s)_{N+1,j+1} = (C_s)_{N,j} - \frac{2De\Delta t}{(\Delta x)^2} ((C_s)_{N+1,j} - (C_s)_{N,j}) - \Delta t (r_A)_{N+1,j} \quad (14)$$

If intra-film-gradient exists, the total sulphide degraded in the biofilm can be calculated by numerical integration as follows:

$$\delta_{j+1} = \delta_j + \frac{AN}{\rho} \frac{\Delta x}{3} \left((r_A)_{0,j} + 4(r_A)_{1,j} + 2(r_A)_{2,j} + \dots + 4(r_A)_{N,j} + (r_A)_{N+1,j} \right) \quad (15)$$

If the results of model 1 and 2 are not significantly different, it can be concluded that the effect of intra-film-gradient can be neglected. But for the opposite, the effect of intra-film-gradient is significant.

3 Research Methodology

3.1 Materials

Raw materials: salak fruit seeds for packing of bio-filter, sludge for source of sulphide degradation bacteria, biogas collected from Integrated Farming Unit, Agricultural Research and Development for Education (KP4) Facility, Gadjah Mada University.

Materials for nutrition: KH_2PO_4 , K_2HPO_4 , $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, CaCl_2 , $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$, $(\text{NH}_4)_2\text{SO}_4$, and yeast extract [29].

Materials for analysis: Zn-Acetic, FeCl_3 and N,N-Dimethyl-1,4-Phenylene Diamonium Diklorida solution, $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$, $\text{CH}_3\text{COONa} \cdot 3\text{H}_2\text{O}$, CH_3COOH , BaCl_2 , and aquadest.

3.2 Research equipment

The main equipment used in this research is the bio-filter packed column. The column for the bio-filter reactor was made of acrylic resin which has an inside diameter of 8.0 cm and a height of 100 cm. The height of SFS packing was 80 cm. The column has 6 port holes at different axial positions for taking samples to analyse sulphide concentration [18].

3.3 Research Procedure

The research procedures include: characterization of salak fruit seeds (SFS), immobilized bacterial cultures on SFS, isolation of bacteria, test of isolate to sulphide oxidation, test of biofilm formation of isolate on SFS, explorative study of isolates immobilized on seeds to degrade sulphide, characterization and identification of isolates superior (all of experimental data no shown in this paper), test of sulphide in biogas degradation in the bio-filter and mathematical modelling as well as testing the mathematical models to experimental data of sulphide elimination in the bio-filter.

4 Result and Discussion

Before being used in the bio-filtration process, after immobilization bacteria on the surface of the SFS, the colonies of bacteria on SFS surface was 1.56×10^8 CFU/ml, after being used for 8 hours in bio-filter process, it has 2.43×10^9 CFU/ml. This shows that during bio-filtration process, the number of bacteria increased, caused by the growth and development of bacteria supported by nutrition from sulphide and nutrition in process bio-filtration [18].

4.1 Elimination of sulfide of biogas in the biofilter

The experiments of removal of sulphide in the biogas using a bio-filter containing the *Bacillus cereus* which forms biofilm on the surface of SFS operated at biogas flow rate of 30 L/h, 48 L/h, 66 L/h and 84 L/h. The axial position observed of the inlet biogas are 0 cm, 20 cm, 40

cm, 60 cm and 80 cm. The sulphide concentration in biogas was varied from 10 ppm to 180 ppm. The relationship between the sulphide concentration and RE versus axial position from gas inlet for biogas flow rate of 30 L/h are shown in Figure 1.

Figure 1. The relationship of the sulphide concentration and RE versus axial position at Q 30 L/h

From Figure 1, the influence of the axial position and operating time can be further discussed. The other figures of the relationship of the sulphide concentration and RE versus axial position at Q 48 L/h, 66 L/h and 84 L/h are presented in Figure 2, Figure 3, and Figure 4. From those figures the influence of the biogas flow rate in the bio-filter could also be studied.

4.1.1 Effect of axial position

H₂S removal efficiency will increase with the increasing distance from the bottom of the column. This happens as a larger distance from the bottom of the column will provide a longer contact time between the biogas and the biofilm, making the removal of H₂S more effective. In this packing column (80 cm long and 8 cm inside diameter, thus L/D=10), the highest H₂S removal efficiency achieved was 97.15%.

Figure 2. The relationship of the sulphide concentration and RE versus axial position at Q 48 L/h

Figure 3. The relationship of the sulphide concentration and RE versus axial position at Q 66 L/h

Figure 4. The relationship of the sulphide concentration and RE versus axial position at Q 84 L/h

4.1.2 Effect of operation time

The H₂S removal efficiency increase with the increasing time of operation, for different initial concentration of H₂S in biogas. This is conceivable since the biofilm grows on SFS surface throughout the column and a larger biofilm mass will consume more H₂S, resulting in the higher H₂S removal. This microbial growth can be visually observed by the increase of the thickness of biofilm formed on the surface of the SFS.

4.1.3 Effect of biogas flow rate

The sulphide removal efficiency in a different position from the gas inlet indicates that the lower gas flow rate results in higher removal efficiency. This fact may be described as the following. As the gas flow rate increased, the contact time between H₂S and microorganism on SFS is shorter, thus only a smaller part of the H₂S could be degraded by the microorganism.

4.1.4 The performance of SFS as a packing material in the bio-filter

The results of this study concluded that SFS can be used as packing material in the bio-filter for elimination of sulphide in the gas phase. It turned out that performance of SFS was comparable with others packing materials studied in the literature.

4.2 Test of the mathematical modelling to experimental data of elimination of H₂S in biogas

Simulations applying the two mathematical models proposed were performed using adjustable values of parameters involved until the results are close to the experimental data obtained. The comparison between the calculated results and the experimental data for the models are shown in Figure 5 and Figure 6. It can be observed that the calculation results using the two models are both close to the experimental data. It means that the two mathematical models proposed are adequate to quantitatively describe H₂S removal from biogas using biofilm on packed bed of SFS.

Figure 5. Comparison of modelling curve to data experiments of model 1

Figure 6. Comparison of modelling curve to data experiments of model 2

To be more comprehensively comparing the suitability of model 1 and model 2 to the experimental data, curves of model 1 and curves of models 2 were closely examined. The trends of the two curves are

significantly different. Curves of model 1 are almost linear, while the curves of model 2 are non-linear. Logical interpretation of the process suggests that the curves of sulphide concentration versus time should be non-linear, because the sulphide concentration decreases due to biodegradation, resulting in the decrease of the rate of biodegradation. So, non-linear trend is more conceivable. As a consequence, model 2 is more conceivable than model 1. The average absolute errors of model 1 and model 2 are comparable, approximately 6 ppm. All in all, this comparison shows that even though both models have comparable accuracies, model 1 and model 2 are significantly different in the trends. Since the difference of model 1 and model 2 are on the consideration of intra-film gradient, it can be concluded that the effect of intra-film gradient needs to be considered.

Even though model 1 is inferior to model 2, but model 1 is still good enough to estimate the value of sulphide concentrations as well as the RE. The advantage of model 1 is the simplicity. It also needs simpler calculation. Time of calculation for model 2 is approximately four times to the one of model 1.

From model 1, it was obtained that: the maximum specific growth rate of bacteria ($\mu_{\max}$) = $9.3\text{E-}7\text{ s}^{-1}$, K_S = $4.0\text{E-}7\text{ g cm}^{-3}$, H_S = 0.7, $Y_{X/S}$ = 60, and mass transfer coefficient a_0 = 0.038 and a_1 = 0.25. Meanwhile for model 2, the maximum specific growth rate of bacteria ($\mu_{\max}$) = $1.8\text{E-}6\text{ s}^{-1}$, half past saturation (α) = $8.0\text{E-}7\text{ g cm}^{-3}$, constant Henry (H_S) = 0.7, yield ($Y_{X/S}$) = 60, effective diffusivity (D_e) = $2\text{E-}4$, and mass transfer coefficient a_0 = 0.0085 and a_1 = 0.2 for all flow rate.

5 Conclusion

This results of research can be concluded that the experiments of elimination of sulphide in biogas using bio-filter column shows that removal efficiency (RE) is affected by the axial position, operation time, biogas flow rate, and the concentration of H₂S in the gas input.

Based on the observation of the trends, it can be concluded that of the two mathematical models proposed, the recommended one is model 2 (assuming there is a gradient of concentration in the biofilm, the flow of gas in the bio-filter quasi-steady-state, the rate of degradation reaction follows Monod's type equation).

The accuracies of model 1 and model 2 are actually comparable since the average absolute errors for both models are approximately 6 ppm.

Comparison to experimental data shows that model 2 works well. For model 2, it was obtained that maximum specific growth rate of bacteria ($\mu_{\max}$) = $1.8\text{E-}6\text{ s}^{-1}$, half past saturation (α) = $8.0\text{E-}7\text{ g / cm}^3$, constant Henry (H_S) = 0.7, yield ($Y_{X/S}$) = 60, effective diffusivity (D_e) = $2\text{E-}4\text{ cm}^2\text{ s}^{-1}$, and mass transfer coefficient a_0 = 0.0085 and a_1 = 0.2 for all flow rates.

Tests of mathematical models against experimental data of the elimination of sulphide in the biogas using a bio-filter containing *Bacillus cereus* bacteria on surface of SFS also indicate that intra-film-gradient needs to be considered, and the gas phase can be assumed to be quasi-steady-state.

Even though not considering intra-film gradient, so that less accurate than model 2, the simpler model 1 is good enough for rough calculation.

The authors would like to acknowledge to Directorate of Research and Technology of Higher Educations of Indonesia, for financial support of the research through research grant of Hibah Bersaing 2015 and Hibah Disertasi Doktor 2016.

References

1. H.R. Amini, D.R. Reinhart, Regional prediction of long-term landfill gas to energy potential. *Waste Manage* 31, 2020–2026 (2011).
2. Yadvika, T.R. Santosh, S. Sreekrishnan, Kohli, V. Rana, Enhancement of Biogas Production from Solid Substrates using Different Techniques - a Review. *Bioresource Technology*, 95, 1-10 (2004).
3. M. Syed, G. Soreanu, P. Falletta, M. Béland, Removal of hydrogen sulfide from gas streams using biological processes—a review, *Can. Biosyst. Eng.* 48 (2006) 2.1–2.14.
4. S. Pipatmanomai, S. Kaewluan, T. Vitidsant, Economic assessment of biogas to electricity generation system with H₂S removal by activated carbon in small pig farm. *Applied Energy*, 86, 669–674 (2008).
5. Boumnijel, H.B. Amor, H. Chekir, N. Hajji, Hydrogen sulphide removal from the effluents of a phosphoric acid production unit by absorption into chlorinated seawater under alkaline conditions, *Comptes Rendus Chimie*, xxx, 1-8(2016).
6. M. Taheri, A. Mohebbi, H. Hashemipour, A.M. Rashidi, Simultaneous absorption of carbon dioxide (CO₂) and hydrogen sulfide (H₂S) from CO₂-H₂S-CH₄ gas mixture using amine-based nanofluids in a wetted wall column, *J. Nat. Gas Sci. Eng.* 28 (2016) 410–417
7. C.C. Lien J.L. Lin, C.H. Ting, Water Scrubbing for Removal of Hydrogen Sulfide (H₂S) Inbiogas from Hog Farms, *Journal of Agricultural Chemistry and Environment* 3, 1-6 (2014).
8. M.R.A. Al Mamun, S. Torii, Removal of Hydrogen Sulfide (H₂S) from Biogas Using Zero-Valent Iron, *Journal of Clean Energy Technologies*, 3, 6, 428-432, (2015).
9. C. Rattanapan, P. Boonsawang, D. Kantachote, Removal of H₂S in downflow GAC biofiltration using sulfide oxidizing bacteria from concentrated latex waste water, *Bioresource Technology*, 100 125-130 (2009).
10. Elias, A. Barona, A. Arreguy, J. Rios, I. Aranguiz, J. Penas, Evaluation of a packing material for the biodegradation of H₂S and product analysis, *Process Biochemistry* 37, 813–820 (2002)..
11. M.A. Deshusses, G. Hamer, and I.J. Dunn, Behavior of biofilters for waste air biotreatment. 1. Dynamic model development. *Environ. Sci. Technol.* 29. 1408–1458 (1995).
12. J.S. Devinny, M.A. Deshusses, and T.S. Webster, *Biofiltration for air pollution control*. Lewis Publishers. Boca Raton. 5–16 (1999).
13. M. Hirai, M. Ohtake, and M. Shoda, Removal Kinetic of Hydrogen Sulfide, Methanotiol and Dimethyl Sulfide by Pear Biofilter, *Journal of Fermentation and Bioengineering* (1990)
14. S. Craig, Microbiology: breaking down biofilm. *Curr Biol*;19:R132–4 (2002).
15. F.P. Chávez, F. Gordillo, C.A. Jerez, Adaptive responses and cellular behaviour of biphenyl degrading bacteria toward polychlorinated biphenyls. *Biotechnol Adv* 2006;24: 309–20 (2006).
16. P. Edmonds, *Microbiology an environmental Perspective*, Collier Macmillan Publisher. London-New York (1978).
17. R.A.S. Lestari, W.B. Sediawan and Sarto, Sulphide Removal from Liquid using Biofilm on Packed Bed of Salak Fruit Seeds, 2nd International Conference on Engineering and Technology for Sustainable Development, Yogyakarta, 13-14 September (2017).
18. G. Spigno, M. Zilli, C. Nicoletta, Mathematical modelling and simulation of phenol degradation in biofilters, *Biochemical Engineering Journal* 19 (2004).
19. S. Majumder, G. Gangadhar, S. Raghuvanshi, S Gupta, Biofilter column for removal of divalent copper from aqueous solutions: Performance evaluation and kinetic modeling *Journal of Water Process Engineering* 6 136–143 (2015).
20. M.B. Jaber, A. Couverta, A. Amrane, F. Rouxel, P. Cloireca, L.E. Dumontd, Biofiltration of H₂S in air—Experimental comparisons of original packing materials and modeling, *Biochemical Engineering Journal* 112, 153–160 (2016).
21. V. Meena, L. Rajendran, S. Kumar, P.G.J. Rani, Mathematical modeling of gas phase and biofilm phase biofilter performance, *egyptian journal of basic and applied sciences* 3, 94–105 (2016).
22. J.M. Santos, E.S. Lopes, N.C.R. Junior, L. Melo de Sa, N.J. Horand, Mathematical modelling of hydrogen sulphide emission and removal in aerobic biofilters comprising chemical oxidation, *water research* 43, 3355 – 3364 (2009).
23. S. Kim, and M.A. Deshusses, Determination of mass transfer coefficients for packing materials used in biofilters and biotrickling filters for air pollution control, *Chemical Engineering Science* 63, 841 – 855 (2008).
24. C. Yang, M.T. Suidan, X. Zhub, B.J. Kimc, G. Zeng, Effect of gas empty bed contact time on performances of various types of rotating drum biofilters for removal of VOCs, *water research* 42,3641–3650 (2008).
25. A.A. Ramirez, S. Bénard, A.G. Fendler, J.P. Jones, M. Heitz, Kinetics of microbial growth and biodegradation of methanol and toluene in biofilters

- and an analysis of the energetic indicators, *Journal of Biotechnology* 138, 88–95 (2008).
26. Visscher, A.D., Li, G.Q., 2008, Toluene removal biofilter modeling: Optimization and case Study, process safety and environment protection 86, 277–282.
 27. G.K. Agarwal, A.K. Ghoshal, Packed bed dynamics during microbial treatment of wastewater: Modelling and simulation, *Bioresource Technology* 99, 3765–3773 (2008).
 28. R.A.S. Lestari, W.B. Sediawan, S. Syamsiah, and Sarto, Hydrogen sulfide removal from biogas using a salak fruit seeds packed bed reactor with sulfur oxidizing bacteria, *Environmental Chemical Engineering Journal*, 4, 2370–2377 (2016).
 29. R.A.S. Lestari, W.B. Sediawan, S. Syamsiah, and Sarto, The Exploratory Study on Sulfide Removal Ability of Sulfur-Oxidizing Bacteria in Biofilm on Salak Fruit Seeds, *International Proceeding of Chemical, Biological & Environmental Engineering, Chemical Engineering and Applications V*, Taipei, Taiwan, 16-19 (2014).