Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2023.29271

284 (2023) 81–86
February

Effects of detention time and ozone dosage on organic content removal and biodegradability index in high salinity leachate

Mega Mutiara Sari[a], Iva Yenis Septiariva[b], Wisnu Prayogo[c], Qomaruddin Helmy[d], I Wayan Koko Suryawan[a,*]

[a]*Department of Environmental Engineering, Faculty of Infrastructure Planning, Universitas Pertamina, Komplek Universitas Pertamina, Jalan Sinabung II, Terusan Simprug, Jakarta 12220, Indonesia, emails: i.suryawan@universitaspertamina.ac.id (I Wayan Koko Suryawan), mega.ms@universitaspertamina.ac.id (M.M. Sari)*
[b]*Sanitary Engineering Laboratory, Study Program of Civil Engineering, Faculty of Engineering, Universitas Sebelas Maret, Jalan Ir Sutami 36A, Kentingan, Surakarta, Indonesia, email: ivayenis@gmail.com*
[c]*Department of Civil Engineering, Faculty of Engineering, Universitas Negeri Medan, Medan, North Sumatra, Indonesia, email: wisnuprayogo@unimed.ac.id*
[d]*Department of Environmental Engineering, Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Bandung 40132, Indonesia, email: helmy@tl.itb.ac.id*

Received 2 May 2022; Accepted 12 December 2022

ABSTRACT

Old leachate from the waste management process can negatively impact the environment if it is not appropriately treated. Commonly, old leachate processing is complicated in view of its low biodegradability, making it impossible to be treated by biological processes. One technology that can increase biodegradability is ozonation. This study aims to determine the effects of dosed ozone on organic removal and the improvement of biodegradability in aged high salinity leachate. This study used leachate samples from the Jungut Batu Landfill in Nusa Lembongan, Klungkung Regency, Indonesia. Something that needs to be considered from the leachate characteristics in the study site included the high salinity value that might lead to low biodegradability. Variations in this study were detention time and ozone dose administration (1, 10, 30, and 100 mg·O_3/min). The initial characteristics of leachate in the study site showed very low biodegradability, reaching 0.084. During the 60-min detention, the maximum chemical oxygen demand (COD) removal could only reach a value of 21.1% (100 mg·O_3/min). At the same time, the ozonation process could achieve an increase in biochemical oxygen demand (BOD)/COD biodegradability of 0.156. Multivariant test results on ozone dosing variations significantly affected organic degradation (BOD and COD) and increased biodegradability.

Keywords: Leachate; Ozonation; Chemical oxygen demand; Biochemical oxygen demand; Biochemical oxygen demand/chemical oxygen demand

1. Introduction

As a result of an exponential rise in the amount of solid waste produced, the solid waste management in Indonesia has become a task that is significantly becoming more difficult for the relevant authorities [1]. This is in relation to the sizeable negative effects on the surrounding environment due to the landfilling activity [2]. In view of a shortage of land used for disposal [3] and more increasing rate of urbanization, an increasing number of landfills are reaching their maximum design capacity earlier than the end of their design lives.

* Corresponding author.

Leachate is liquid waste from landfills that can be sourced from rainwater or the degradation of the waste itself [4]. Commonly, the content of organic matter in leachate is very high. The typical volume of leachate produced by a ton of municipal solid waste with a moisture percentage of 30%–35% is 0.2 m^3 (or around 0.05–0.07 tons) [5]. By contrast, fresh leachate has a high chemical oxygen demand (>10,000 mg/L), a high biochemical oxygen demand (BOD_5)/chemical oxygen demand (COD) ratio (>0.3), a low pH (6.5), and a high concentration of biodegradable organic materials, particularly volatile fatty acids (VFA) [6]. In addition, heavy metal materials due to degradation from landfilled waste indicate that leachate is toxic [7]. Old leachates are classified as stabilized and are distinguished by characteristics including a relatively low COD (<4,000 mg/L), slightly basic pH (7.5–8.5), low biodegradability (BOD_5/COD 0.1), and high molecular weight compounds. Stabilization occurs as a result of an increase in the age of the landfill and the breakdown of volatile fatty acids in the landfill leachate by anaerobe bacteria over a period of 10 y [8]. Therefore, leachate containing these hazardous substances can cause the potential contamination of both surface and groundwater [9]. Furthermore, the amount of hazardous content in wastewater can cause adverse effects on health and the environment if it is channelled into water bodies without any prior treatment [10].

Leachate is a liquid with an unpleasant odour and dark colour, which generally contains high organic and inorganic materials. The leachate characteristics are influenced by landfill age, rainfall and percolation rate of water entering the landfill, waste quantity, type, waste composition, landfill stabilization level, landfill humidity, position, and sampling time [11]. The stages of the degradation process in landfills consist of the initial phase or the aerobic-transition phase (0–5 y), the acid formation phase (5–10 y), the methane fermentation phase (10–20 y), and the final maturation phase (>20 y) [12].

The salinity concentration in water is determined by ions such as chloride, carbonate, bicarbonate, sulphate, sodium, calcium, and magnesium [13]. The salinity level in the waste or leachate components depends upon the content of chloride (Cl^-) [14]. Chloride here can affect the plasmolysis process in the cell walls of microorganisms to deal with osmoregulation problems in response to external osmotic changes. Thus, leachate with high salinity can cause microorganisms used as leachate treatment biologically not to be able to decompose organic matter, resulting in a decrease in efficiency at the leachate treatment plant at Benowo Landfill in Surabaya [15].

The leachate treatment in landfills uses a biological system in the form of a stabilization pond [16]. The BOD/COD ratio considered easy to process by biological means is 0.3 [17] or greater [18]. Therefore, landfill leachate with a low BOD/COD ratio should be treated chemically [19]. One of the chemical processing through oxidation using the principle of oxidation is ozone technology. Previously research had not discussed the effect of ozone doses on leachate degradation with high salinity levels [20], especially for leachate on small islands.

The ozone reaction can be direct or indirect [21]. The direct reaction is the reaction of ozone molecules with various chemicals; in contrast, the indirect reaction occurs through free radical reactions formed from ozone decomposition [22]. The ozone molecule itself is quite strong to react directly with organic compounds because ozone is a strong oxidant in water but has properties so that not all pollutants can react with ozone. In turn, this study aimed to determine the effects of dosed ozone on organic removal and the improvement of biodegradability in old high salinity leachate.

2. Material and method

2.1. Sampling

The samples came from leachate in Jungut Batu Landfill (Fig. 1), located on Nusa Lembongan Island, Klungkung Regency, Bali Province. Jungut Batu Landfill has been operating since 2003 and has an area of 1.84 Ha. Waste management carried out in Nusa Lembongan collects waste from sources to public places collected at temporary disposal sites.

2.2. Experimental set-up

The research was conducted in a semi-batch where the supply of ozone gas was carried out continuously to a batch contactor containing 1.5 L of leachate. The concentrated leachate samples were kept tightly sealed in a cool place (at 8°C–13°C) until further use [5]. This was done to make any changes in the chemical and biological properties of the samples able to be kept to a minimum.

Batch experiments provided information about the critical point of decreasing concentration with the most significant gradient before experiencing a slope. The series of research tools used in this study included oxygen cylinders with a capacity of 2 m^3, which would flow O_3 at a rate of 1, 10, 30, and 100 mg/min through an ozone generator. The ozone contactor was also equipped with a valuable valve for taking water samples for 60 min [17]. The remaining ozone in the gas phase was decomposed in the ozone decomposer, containing a KI solution to capture the remaining ozone (Fig. 2).

A device destroying ozone was used on the surplus of ozone produced by the contacting reactor. Through a catalytic process, it converted the ozone into oxygen, which was then expelled through the vent. Before being sent to the ozone destructor, certain experiments required that this excess gas be routed through a KI solution, also known as an ozone trap to accurately measure the amount of excess ozone present [23].

2.3. Sample analysis

The effectiveness of the ozonation process was determined based upon the measurement of BOD, COD, and BOD/COD parameters. COD analysis was carried out by taking 10 mL of sample into a 250 mL Erlenmeyer, and the addition of 0.2 g of $HgSO_4$ powder. Furthermore, 5 mL of 0.25N potassium dichromate solution and 15 mL of sulphuric acid – silver sulphate reagent was slowly added while cooled in cooling water. It began by heating using an oven for 2 h at a temperature of 150°C before being cooled at a

Fig. 1. Location of leachate collection for treatment with ozonization process.

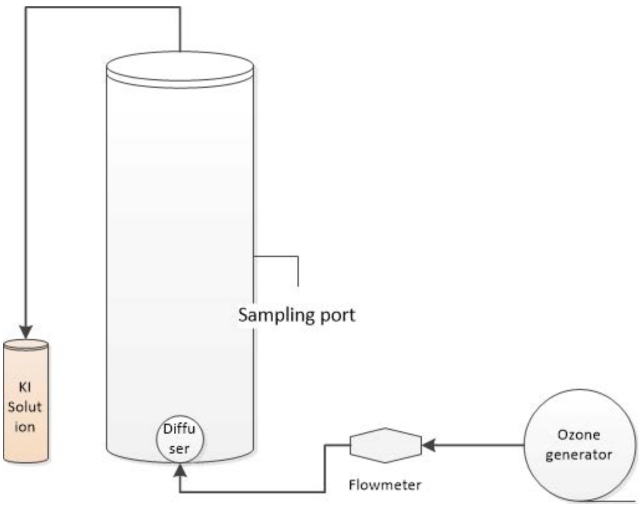

Fig. 2. Experimental reactor set-up.

room temperature, and being added with 2 to 3 drops of ferroin indicator, titrated with 0.1 N FAS (Ferrous Ammonium Sulfate) solution to brownish-red colour, and noted the need for FAS solution. Furthermore, the same steps were carried out for distilled water as a blank for SNI 06-6989.15-2004.

8 bottles of dissolved oxygen were prepared, the sample solution were then put without filtering, and the solid silica membrane (1, 3, and 5 g) was filtered into each bottle until it overflowed, and then tightly closed to avoid air bubbles. Palm oil liquid waste was then prepared and it was added with 1 mL of $MnSO_4$ and 1 mL of KOH-KI and shaken until a brownish white precipitate was formed. Then, 1 mL of H_2SO_4 was added, shaken and allowed to stand until changing into brown. Samples were taken as much as 100 mL, and then 0.0125 N sodium thiosulfate was added to form a pale-yellow solution. The solution was then added with 5 drops of starch indicator and titrated with 0.0125 N sodium thiosulfate to develop a colourless solution. The volume of sodium thiosulfate used was equal to the final dissolved oxygen value (SNI 6989-72.2009).

3. Results and discussion

Table 1 presents the characteristics of leachate in the Jungut Batu Landfill. The result showed that nitrogen content in leachate samples was very high. This indicated that 70% of the waste composition in Indonesia is an organic material [24], so heterotrophic bacteria will change organic nitrogen. While the comparison of BOD/COD in the sample was only 0.084, indicating the domination of the content of non-biodegradable organic matter against the leachate. The BOD/COD ratio was less than 0.5, indicating that the treatment should not use biological but physical–chemical processes [25].

The COD measurement graph can be seen in Fig. 3. Based on the figure, the four variations provided a trend with the same tendency. The critical point in the conventional ozonation process was at the 10th min when the highest dose of ozone was 100 mg/min. The COD concentration reached 5,873 mg/L, while up to the 10th min, the COD removal efficiency reaching 21.1%. This result is comparable to prior

Table 1
Characteristics of leachate as initial ozonization process

Parameters	Value	Standard [24]
pH	5.36	6–9
BOD, mg/L	477.6	150
COD, mg/L	10,699	300
TSS, mg/L	358.2	100
N total, mg/L	423	60
Mercury, mg/L	0.00237	0.005
Cadmium, mg/L	–	0.1
Salinity, $^0/_{00}$	6.658	34
BOD/COD	0.084	–

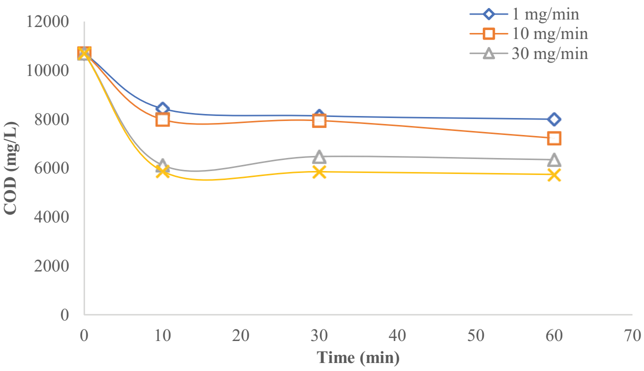

Fig. 3. Changes in COD concentration for each variation of ozone dosage.

study that found that without salination, COD removal might reach 26.7% [26]. OH$^{\bullet}$ was more dominant than ozone itself so this species played a more dominant role with better oxidizing power [27]. After the reaction between OH$^{\bullet}$ and organic matter occurred, the fraction of organic matter became a carbon centre radical [28]. The response of the carbon centre radical with oxygen caused the formation of superoxide radical [29], which then reacted with ozone to form an OH radical again. In the process that was being evaluated, an increase in the concentration of O_3 resulted in an improvement in the rate of COD and BOD_5 removal [30]. Another study found that optimum conditions comprised a reaction period of 90 min to achieve 79% COD removal with Fenton's reagent [20], 210 min to archive 72% COD removal with persulfate [31], in advanced ozone oxidation, however our results only demonstrated 21.1% removal.

The kinetics of the rate of change of concentration in the electrocoagulation reactor followed order 1, with COD removal seen increasing with the addition of ozone dose (Fig. 4). This showed that the greater the ozone dose, the greater the COD removal rate. Indirectly, it is also known that the greater the dose of ozone, the hydraulic loading rate (HLR) that occurs, and the longer the time required by the sample to achieve the optimum COD removal. The actual detention time of the reactor also increased with the decrease in the HLR, which then affected the determination of the reactor effluent sampling time. HLR is a one key indicator of the landfill leachate treatment process [32]. The results

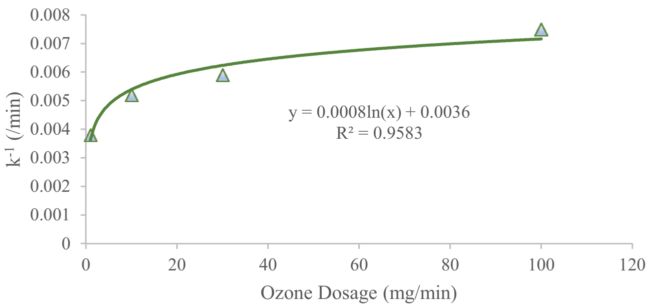

Fig. 4. Relationship of change in removal rate COD for each variation of ozone dosage.

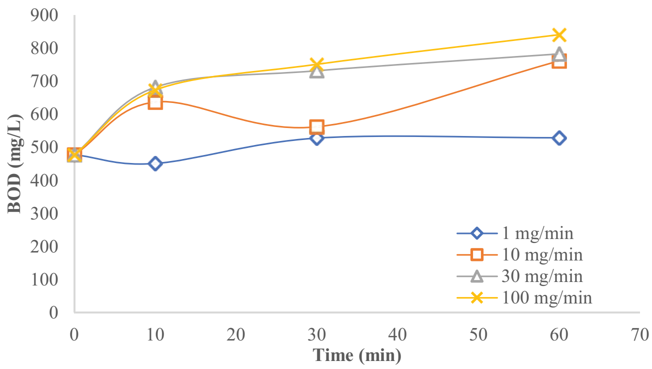

Fig. 5. Changes in BOD concentration for each variation of ozone dosage.

of the investigation demonstrated that using oxidation to remove pollutants speeds up the process for wastewater treatment has good and synergistic effects concurrently [30].

Another parameter that measures the effectiveness of the ozone process is BOD, which shows an indicator of organic matter that can be biologically degraded. The results of BOD measurements for the three variations can be seen in Fig. 5. An increase in the ratio of BOD concentration in leachate in the ozonation process indicates a decrease in the levels of complex organic compounds that are difficult to biodegrade [33]. The best and fair reaction time, according to another study, is 4 min [30]. The test results showed that oxidation had a positive effect on process leachates by lowering the BOD_5/COD ratio by 30%; as a result, it reduced the oxygen requirement during treatment. Due to the high biodegradability of leachates from the composting process, this reaction can be used as a pre-treatment step before sending them to a wastewater treatment facility [30].

Based on the level of biodegradability, the leachate used in this study was categorized as having a very low level of biodegradability with a BOD/COD ratio of 0.084 (Fig. 6). The level of leachate biodegradability studied indicated that biological treatment was less profitable than chemical treatment. The age of the leachate in this study can be seen from the BOD/COD ratio of 0.156, indicating that the leachate was more biodegradable compared to the one in the initial condition.

The absorption and desorption mechanism of ozone gas occurs so that mass transfer occurs from the gas phase (ozone) into the liquid phase (wastewater) and vice versa.

Table 2
Results of analysis of the effect of detention time and ozone dosage on BOD, COD, and biodegradability concentrations

Variable			Sum of squares	Df	Mean square	*F*	*P*-value
Detention time	BOD	Between groups	29,619.287	2	14,809.64		
		Within groups	131,223.743	9	14,580.42	1.016	0.4
		Total	160,843.029	11			
	COD	Between groups	201,242.308	2	100,621.2		
		Within groups	11,763,883.94	9	1,307,098	0.077	0.927
		Total	11,965,126.25	11			
	BOD/COD	Between groups	0.001	2	0		
		Within groups	0.009	9	0.001	0.471	0.639
		Total	0.01	11			
Ozone dosage	BOD	Between groups	117,321.189	3	39,107.06		
		Within groups	43,521.84	8	5,440.23	7.188	0.012
		Total	160,843.029	11			
	COD	Between groups	11,427,564.65	3	3,809,188		
		Within groups	537,561.602	8	67,195.2	56.688	0.00
		Total	11,965,126.25	11			
	BOD/COD	Between groups	0.008	3	0.003		
		Within groups	0.001	8	0	16.95	0.001
		Total	0.01	11			

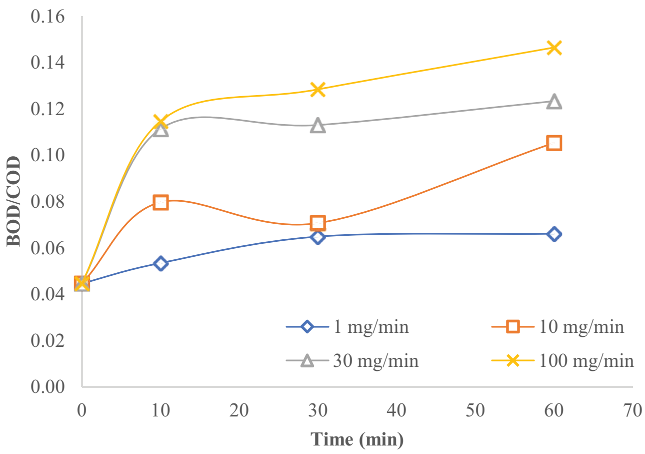

Fig. 6. Changes in biodegradability for each variation of ozone dosage.

The amount/rate of mass transfer depends, among others: on solubility, pH, initial concentration, contact time, flow direction, and the type and shape of the filling material. In this study, detention time had no significant effect on BOD, COD, or BOD/COD (Table 2). This is in contrast to other studies, which stated that a more effective way to increase contact time is to increase the contact area between the gas phase and the liquid phase by decreasing the size of the ozone gas bubbles dispersed in solution [34].

While the ozone dose has a stronger significance value than the detention time (Table 2), ozonation is an advanced oxidation process widely studied as a leachate treatment. The ozonation process is a continuation of the coagulation–flocculation process. The single process, oxidation with ozone, is ineffective due to the complexity of the leachate composition and the very high dose of ozone. Ozonation is a strong oxidizing agent with high reactivity towards organic substances that are difficult to degrade. Ozone produces hydroxyl radicals that have a higher oxidation potential, which can oxidize organic compounds that are difficult to degrade. Thus, the ozonation method allows the transformation of compounds that are difficult to degrade into biodegradable products [35].

4. Conclusion

The biodegradability of the leachate studied had very low characteristics, reaching 0.084. The detention time of 60 min maximum COD removal could only reach 21.1% at a dose of 100 mg/min of ozone. The ozonation process was able to achieve an increase in biodegradability of 0.156. The results of the multivariant unit on the variation of the dose of ozone showed a very significant effect on decreasing BOD and COD and increasing biodegradability. Ozonation with advanced oxidation processes has been intensively researched as a saline leachate treatment. The ozonation process is a continuation of the coagulation–flocculation process. Due to the complexity of the leachate composition and the extremely high dose of ozone, the single procedure, oxidation with ozone, is inefficient. Ozonation is a powerful oxidizing agent with a high reactivity to organic compounds that are difficult to breakdown. Ozone generates hydroxyl radicals with a greater oxidation potential, which can oxidize organic molecules that are difficult to breakdown. Future study can concentrate on the necessary development, particularly on the smallest island's limited land and energy resources. In some circumstances, research in leachate treatment on small islands has resulted in viable technologies. These technologies have the potential to help reduce the threat of marine pollution.

References

[1] I.W.K. Suryawan, I.Y. Septiariva, E.N. Fauziah, B.S. Ramadan, F.D. Qonitan, N.L. Zahra, A. Sarwono, M.M. Sari, K.K. Ummatin, L.J. Wei, Municipal solid waste to energy: palletization of paper and garden waste into refuse derived fuel, J. Ecol. Eng., 23 (2022) 64–74.

[2] W.L. Cheong, Y.J. Chan, T.J. Tiong, W.C. Chong, W. Kiatkittipong, K. Kiatkittipong, M. Mohamad, H. Daud, I. Wayan Koko Suryawan, M.M. Sari, J.W. Lim, Anaerobic co-digestion of food waste with sewage sludge: simulation and optimization for maximum biogas production, Water, 14 (2022) 1075, doi: 10.3390/w14071075.

[3] M.M. Sari, I.Y. Septiariva, E.N. Fauziah, K.K. Ummatin, Q.A.M.O. Arifianti, N. Faria, J.-W. Lim, I.W.K. Suryawan, Prediction of recovery energy from ultimate analysis of waste generation in Depok City, Indonesia, Int. J. Electr. Comput. Syst. Eng., 13 (2023) 1, doi: 10.11591/ijece.v13i1.pp1-8.

[4] H. Ke, C.S. Zhang, J. Hu, R. Qin, Y.M. Chen, J.W. Lan, Evaluation of leachate production and level in municipal solid waste landfills considering secondary compression, Environ. Sci. Pollut. Res., 29 (2022) 20542–20555.

[5] H. Wang, Y.-n. Wang, X. Li, Y. Sun, H. Wu, D. Chen, Removal of humic substances from reverse osmosis (RO) and nanofiltration (NF) concentrated leachate using continuously ozone generation-reaction treatment equipment, Waste Manage., 56 (2016) 271–279.

[6] S.F. Ramli, H.A. Aziz, F.M. Omar, M.S. Yusoff, H. Halim, M.A. Kamaruddin, K.S. Ariffin, Y.-T. Hung, Reduction of COD and highly coloured mature landfill leachate by tin tetrachloride with rubber seed and polyacrylamide, Water, 13 (2021) 3062, doi: 10.3390/w13213062.

[7] P. Wijekoon, P.A. Koliyabandara, A.T. Cooray, S.S. Lam, B.C.L. Athapattu, M. Vithanage, Progress and prospects in mitigation of landfill leachate pollution: risk, pollution potential, treatment and challenges, J. Hazard. Mater., 421 (2022) 126627, doi: 10.1016/j.jhazmat.2021.126627.

[8] F. Javier Rivas, F. Beltrán, F. Carvalho, B. Acedo, O. Gimeno, Stabilized leachates: sequential coagulation–flocculation + chemical oxidation process, J. Hazard. Mater., 116 (2004) 95–102.

[9] I.Y. Septiariva, I.W.K. Suryawan, Development of the water quality index (WQI) and hydrogen sulfide (H_2S) for assessments around the Suwung landfill, Bali island, J. Sustainability Sci. Manage., 16 (2021) 137–148.

[10] I Wayan Koko Suryawan, A. Rahman, J.-W. Lim, Q. Helmy, Environmental impact of municipal wastewater management based on analysis of life cycle assessment in Denpasar City, Desal. Water Treat., 244 (2021) 55–62.

[11] M.A. Kamaruddin, M.S. Yusoff, L.M. Rui, A.M. Isa, M.H. Zawawi, R. Alrozi, An overview of municipal solid waste management and landfill leachate treatment: Malaysia and Asian perspectives, Environ. Sci. Pollut. Res., 24 (2017) 26988–27020.

[12] E.S. Yusmartini, D. Setiabudidaya, Ridwan, Marsi, Faizal, Characteristics of leachate at Sukawinatan Landfill, Palembang, Indonesia, J. Phys. Conf. Ser., 423 (2013) 012048, doi:10.1088/1742-6596/423/1/012048.

[13] S. Selvakumar, K. Ramkumar, N. Chandrasekar, N.S. Magesh, S. Kaliraj, Groundwater quality and its suitability for drinking and irrigational use in the Southern Tiruchirappalli district, Tamil Nadu, India, Appl. Water Sci., 7 (2017) 411–420.

[14] S. Kanmani, R. Gandhimathi, Investigation of physicochemical characteristics and heavy metal distribution profile in groundwater system around the open dump site, Appl. Water Sci., 3 (2013) 387–399.

[15] A. Chusnun, I. Warmadewanthi, Effectiveness of *Typha angustifolia* and *Eichhornia crassipes* in processing leachate with constructed wetland system, Pros. Semin. Nas. Manaj. Teknol., XVIII (2013) 1–7.

[16] E. Noerfitriyani, D.M. Hartono, S.S. Moersidik, I. Gusniani, Leachate characterization and performance evaluation of leachate treatment plant in Cipayung landfill, Indonesia, IOP Conf. Ser.: Earth Environ. Sci., 106 (2018) 12086, doi: 10.1088/1755-1315/106/1/012086.

[17] I Wayan Koko Suryawan, G. Prajati, A.S. Afifah, M.R. Apritama, NH_3–N and COD reduction in Endek (Balinese textile) wastewater by activated sludge under different DO condition with ozone pretreatment, Walailak J. Sci. Technol. (WJST), 18 (2021) 1–11, doi: 10.48048/wjst.2021.9127.

[18] A.S. Afifah, I Wayan Koko Suryawan, A. Sarwono, Microalgae production using photo-bioreactor with intermittent aeration for municipal wastewater substrate and nutrient removal, Commun. Sci. Technol., 5 (2020) 107–111.

[19] Z. Salem, K. Hamouri, R. Djemaa, K. Allia, Evaluation of landfill leachate pollution and treatment, Desalination, 220 (2008) 108–114.

[20] S.S. Abu Amr, H.A. Aziz, M.N. Adlan, M.J.K. Bashir, Optimization of semi-aerobic stabilized leachate treatment using ozone/Fenton's reagent in the advanced oxidation process, J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng., 48 (2013) 720–729.

[21] Q. Helmy, I Wayan Koko Suryawan, S. Notodarmojo, Ozone-Based Processes in Dye Removal, S.S. Muthu, A. Khadir, Eds., Advanced Oxidation Processes in Dye-Containing Wastewater, Sustainable Textiles: Production, Processing, Manufacturing & Chemistry, Springer, Singapore, 2022, pp. 91–128, doi: 10.1007/978-981-19-0987-0_6.

[22] Y.-P. Chiang, Y.-Y. Liang, C.-N. Chang, A.C. Chao, Differentiating ozone direct and indirect reactions on decomposition of humic substances, Chemosphere, 65 (2006) 2395–2400.

[23] A. Jabesa, P. Ghosh, Oxidation of bisphenol-A by ozone microbubbles: effects of operational parameters and kinetics study, Environ. Technol. Innovation, 26 (2022) 102271, doi: 10.1016/j.eti.2022.102271.

[24] H. Pasang, G.A. Moore, G. Sitorus, Neighbourhood-based waste management: a solution for solid waste problems in Jakarta, Indonesia, Waste Manage., 27 (2007) 1924–1938.

[25] G. Tchobanoglous, H. Theisen, S. Vigil, T. George, Integrated Solid Waste Management: Engineering Principles and Management Issues, McGraw-Hill Companies, New York, 1993.

[26] S.S. Abu Amr, H.A. Aziz, M.J.K. Bashir, Application of response surface methodology (RSM) for optimization of semi-aerobic landfill leachate treatment using ozone, Appl. Water Sci., 4 (2014) 231–239.

[27] F. Lin, Z. Wang, Z. Zhang, Y. He, Y. Zhu, J. Shao, D. Yuan, G. Chen, K. Cen, Flue gas treatment with ozone oxidation: an overview on NO_x, organic pollutants, and mercury, Chem. Eng. J., 382 (2020) 123030, doi: 10.1016/j.cej.2019.123030.

[28] M.R. McGillen, W.P.L. Carter, A. Mellouki, J.J. Orlando, B. Picquet-Varrault, T.J. Wallington, Database for the kinetics of the gas-phase atmospheric reactions of organic compounds, Earth Syst. Sci. Data, 12 (2020) 1203–1216.

[29] J. Wang, S. Wang, Reactive species in advanced oxidation processes: formation, identification and reaction mechanism, Chem. Eng. J., 401 (20220) 126158, doi: 10.1016/j.cej.2020.126158.

[30] M. Gliniak, D. Polek, M. Wołosiewicz-Głąb, Advanced oxidation treatment of composting leachate of food solid waste by ozone-hydrogen peroxide, J. Ecol. Eng., 20 (2019) 203–208.

[31] S.S. Abu Amr, H.A. Aziz, M.N. Adlan, M.J.K. Bashir, Pretreatment of stabilized leachate using ozone/persulfate oxidation process, Chem. Eng. J., 221 (2013) 492–499.

[32] S.Q. Aziz, H.A. Aziz, A. Mojiri, M.J.K. Bashir, S.S.A. Amr, Landfill leachate treatment using sequencing batch reactor (SBR) process: limitation of operational parameters and performance, Int. J. Sci. Res. Knowl., 1 (2013) 34–43.

[33] S. Li, Y. Yang, H. Zheng, Y. Zheng, T. Jing, J. Ma, J. Nan, Y. Kit Leong, J.-S. Chang, Advanced oxidation process based on hydroxyl and sulfate radicals to degrade refractory organic pollutants in landfill leachate, Chemosphere, 297 (2022) 134214, doi: 10.1016/j.chemosphere.2022.134214.

[34] B. Langlais, D.A. Reckhow, D.R. Brink, Ozone in Water Treatment: Application and Engineering, C&C Press Taylor & Francis Group, Denver, United Kingdom, 1991.

[35] V. Oloibiri, I. Ufomba, M. Chys, W.T.M. Audenaert, K. Demeestere, S.W.H. Van Hulle, A comparative study on the efficiency of ozonation and coagulation–flocculation as pretreatment to activated carbon adsorption of biologically stabilized landfill leachate, Waste Manage., 43 (2015) 335–342.