RESEARCH ARTICLE

The treatment of stabilized landfill leachate using iron-activated persulfate and peroxymonosulfate oxidation

Ahmad Razali Ishak [a, b], Sharifah Mohamad [a], Kheng Soo Tay [a,*]

[a] *Department of Chemistry, Faculty of Science, Universiti Malaya, 50603 Kuala Lumpur, Malaysia*
[b] *Centre of Environmental Health and Safety, Faculty of Health Sciences, Universiti Teknologi MARA cawangan Selangor, Kampus Puncak Alam, 42300 Selangor, Malaysia*

* *Corresponding author: khengsoo@um.edu.my*

Graphical abstract

Abstract

The feasibility of sulfate radical-based advanced oxidation process (SR-AOP) in the reduction of chemical oxygen demands (COD) of pre-treated landfill leachate was evaluated. Nearly 70 % of COD from raw leachate was successfully removed by coagulation-flocculation pre-treatment. However, the COD concentration was still exceeded the discharge limit for most of the countries and required further treatment. The pre-treated leachate was then further treated with SR-AOP. In this work, Fe(II) activated persulfate (PS) and peroxymonosulfate (PMS) were used to generate the sulfate radical. The results indicated that the COD reduction efficiencies for both PMS/Fe(II) and PS/Fe(II) treatment systems were influenced by the oxidant to Fe(II) ratio, the dosage of oxidants, and reaction time. The initial pH of leachate and types of oxidants did not significantly influence the COD reduction. By using the optimal condition, nearly 83 and 84% of COD were reduced by the coagulation-flocculation coupled with SR-AOP. Ecotoxicity analysis by zebrafish showed that the toxicity was significantly reduced after coagulation-flocculation was done. However, the formation of residual sulfate ion after SR-AOP treatment slightly increased the toxicity of the final effluent.

Keywords: Chemical Oxygen Demand, sulfate radical, coagulation-flocculation, advanced oxidation process, ecotoxicity

INTRODUCTION

Landfilling is the most common method of solid waste management throughout the world (Hoornweg and Bhada-Tata, 2012). One of the main environmental issues of landfilling is the generation of landfill leachates. Landfill leachates contain high organic content and a wide range of chemicals, including hazardous substances such as heavy metals (Bashir *et al.,* 2015). The untreated leachates can emerge into the environment and cause serious soil and water pollutions (Deng and Englehardt, 2006). Therefore, it is critical to apply an efficient water treatment method to treat hazardous leachates to protect the environment.

In the landfill treatment plant, leachates are commonly treated biologically as the primary treatment process. Unfortunately, the biological treatment has been found to be ineffective in degrading high molecular weight compounds in leachates (Trebouet *et al.,* 2001). As a result, coagulation-flocculation is often added to the leachate treatment to enhance organic content removal. However, this method is not always satisfactory in reducing organic content to the level that satisfied the environmental quality standards (Kurniawan *et al.,* 2006). As a result, recent researches have been focused on the development of advanced oxidation processes (AOPs) to enhance the efficiency of leachate treatment. These methods including Fenton, ozone-based AOP, UV/H_2O_2, and photocatalysis (Liu *et al.*, 2016; Jung *et al.,* 2017; Hassan *et al.,* 2016).

Recently, SR-AOP has drawn an increasing attention in the degradation of various organic pollutants (Asaithambi *et al.,* 2017). During SR-AOP, sulfate radical (SR) (E^o = 2.5-3.1 V) is one of the main reactive species that degrade organic compounds in water. SR can be produced using persulfate (PS) and peroxymonosulfate (PMS) through numerous activation methods such as heat, the addition of transition metals, and ultraviolet light. (Zhou *et al.,* 2015). In contrast to the more commonly used hydroxyl radical (·OH), which can be deactivated easily by water matrices, the organic compound can selectively react with SR through electron transfer reaction (Matzek and Carter 2016). The unselective behavior of ·OH tends to attack any organic matter, and consequently, the ·OH is quickly spent (Deng and Zhao, 2015). Meanwhile, the SR has been reported to have a longer radical lifetime (30-40 µs) and thus increases the probability to react with the non-biodegradable pollutant and the removal of organic content (Zhou *et al.,* 2015).

SR-AOP was found to be efficient in degrading organic pollution such as pharmaceuticals in water, but most of these studies intensively focused on the treatment of individual compound (Anipsitakis *et al.,* 2006; Olmez-Hanci *et al.,* 2013; Ghanbari *et al,* 2016). The application of SR-AOP in real wastewater treatment is rarely reported. Recently, Fagier *et al.,* (2016) reported that the high efficiency of SR-AOP in the removal of organic matter in distillery wastewater. This study showed that the efficiency of organic content removal in the distillery wastewater could be reduced at neutral pH. Therefore, SR-AOP has been classified as one of the potential water treatment methods to be

considered for industrial scale water treatment (Ghanbari and Moradi, 2017). This study aimed to evaluate the efficiency of SR-AOP in the degradation of COD in pre-treated stabilized landfill leachate (SLL). The effects of the main parameters, such as dosage, pH, type of oxidant to ferrous ion ratio, and reaction time were examined. Also, zebrafish (*Danio rerio*) was used to evaluate the ecotoxicity of the SR-AOP treated landfill leachate.

EXPERIMENTAL

Chemicals and reagents

Sodium hydroxide was purchased from Fluka (Germany). $FeSO_4.7H_2O$ (99.5 %), while potassium peroxymonosulfate (PMS) (99 %), and potassium persulfate (PS) (99 %) were obtained from Acros Organics (USA). H_2SO_4 (95-97 %), $FeCl_3$, and sand were purchased from Merck (Germany).

Landfill leachate pre-treated by coagulation-flocculation

SLL sample was collected from a sanitary landfill in Selangor, Malaysia. The SLL was first treated with coagulation-flocculation treatment with 1.4 g/L of $FeCl_3$ as coagulant at pH 6. The coagulation-flocculation pre-treatment was started with the agitation of the mixture for 2 min at 200 rpm, followed by slow mixing for 30 min at 50 rpm. Then, the agitation was stopped, and the floc was left to settle for 1 h. After that, the treated SLL was then filtered through a sand filter before treated with SR-AOP.

Sulfate radical based advanced oxidation process

The SR-AOP reactions (PMS/Fe(II) and PS/Fe(II)) were carried out in batch mode at room temperature. At first, 25 mL of pre-treated SLL was added into a glass vial. Then, oxidants (PS or PMS) and catalyst ($FeSO_4.7H_2O$) were added. By using an orbital shaker, the mixtures were shaken at 150 rpm. In this study, the effect of four SR-AOP operating conditions on COD reduction was investigated. These parameters were oxidants to Fe(II) ratio (PMS:Fe(II) and PS:Fe(II)), pH, oxidant dosage, and reaction time. PMS:Fe(II) and PS:Fe(II) were determined by varying the concentration of Fe(II) at 12 mM of PS and PMS. Then, by using the optimized ratio, the effect of pH was conducted by adjusting the pH of pre-treated SLL using H_2SO_4 or NaOH. The effect of oxidant dosage was then investigated by varying the concentration of PS and PMS from 5 to 20 mM at pre-determined PMS:Fe(II), PS:Fe(II), and pH. SR-AOP reactions for the above operating parameter were performed at 1 h reaction time. For reaction time optimization, the experiment was carried out from 0.5 until 5 h. All data from this study were analyzed using descriptive statistics method.

Characterization of leachates

All the physicochemical parameters of SLL were determined according to the APHA (2012) standard method. The turbidity and color were determined by Spectroquant Colorimeter Move-100 (Merck). COD measurement was conducted using the closed tube digestion method (Westwood 2007). Total Organic Carbon (TOC) was analyzed using the TOC analyzer (TOC-L, Shimadzu, Japan). The concentration of anions was determined using an Ion Chromatograph (Dionex ICS-1100).

Toxicity investigation

Acute toxicity of the treated leachate was evaluated by using zebrafish. This species has been classified as a model vertebrate for chemical and aquatic toxicity testing (Moșneang *et al.,* 2014). The various pathway that controls the development of zebrafish is highly correlated with human physiology (Hollert and Keiter, 2015). Acute toxicity testing was conducted based on OECD Guideline (OECD, 2013). Ten similar size of fishes were transferred into a 5 L container for each concentration. The experiment was performed in triplicate and conducted for 48 h and 96 h without feeding. The mortality of the fish was recorded for LC_{50} determination. 96 h LC_{50} were converted to toxic unit values (TU) according to the following equation and then considered as an indication of the comparison.

$$Toxicity\ Unit\ (TU) = \frac{100\%}{LC_{50}} \quad (1)$$

RESULTS AND DISCUSSION
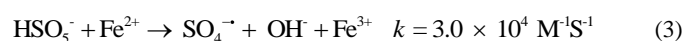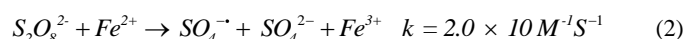
Landfill leachate characteristic

Coagulation-flocculation experiment was performed using $FeCl_3$ as coagulant as described by Amor *et al.,* (2015). The main chemical characteristics of the raw and pre-treated SLL are shown in Table 1. The results indicated that nearly 100 and 94% of turbidity and color were successfully reduced through coagulation-flocculation. The organic content (TOC and COD) was also significantly reduced after coagulation-flocculation. However, it was found that COD concentration was not complying with the allowable discharge standard in many countries. Kurniawan *et al.,* (2006) reported that the maximum discharge standard of landfill leachate in the USA, Germany, France, Hong Kong, and South Korea, were 200 mg/L of COD. In this study, the COD concentration after coagulation-flocculation was 276 mg/L. The pre-treated SLL was then treated with SR-AOP.

Table 1 Chemical characteristic of SLL and pre-treated SLL.

Parameter	SLL	Pre-treated SLL
pH	7.59 ± 0.08	4.53 ± 0.05
COD (× 10^2 mg/L)	11.2 ± 0.2	2.8 ± 0.1
TOC (× 10^2 mg/L)	3.56 ± 0.06	1.07 ± 0.04
Turbidity (× 10^2 FAU)	3.0 ± 0.1	*Not detected*
Colour (× 10^2 Pt/Co)	50.98 ± 0.02	3.1 ± 0.1

SR-AOP optimization

In this study, two different types of oxidants, namely PS ($S_2O_8^{2-}$) and PMS (HSO_5^-) were used to generate SR. In water, these oxidants showed high solubility and stability at different pHs (Zhou *et al.,* 2015; Fagier *et al.,* 2016). Therefore, this method can be an added advantage to leachate treatment since the leachate may turn acidic after coagulation-flocculation. In this study, Fe(II) was used as a catalyst to activate the SR because of its low toxic and environmentally friendly (Rastogi *et al.* 2009). The SR formation from Fe(II) activated PS and PMS are illustrated by the following equations:

$$S_2O_8^{2-} + Fe^{2+} \rightarrow SO_4^{-\bullet} + SO_4^{2-} + Fe^{3+} \quad k = 2.0 \times 10\ M^{-1}S^{-1} \quad (2)$$

$$HSO_5^- + Fe^{2+} \rightarrow SO_4^{-\bullet} + OH^- + Fe^{3+} \quad k = 3.0 \times 10^4\ M^{-1}S^{-1} \quad (3)$$

The effect of the operating condition of SR-AOP on the COD reduction was examined by varying the PS:Fe(II) and PMS:Fe(II) ratios, pH, oxidant's dosage, and reaction time (Fig. 1). The effect of oxidant:Fe(II) ratio was investigated by varying the Fe(II) concentration from 1 to 24 mM. The oxidants (PS and PMS) concentration was fixed at 12 mM. The result from these experiments was presented as the percentage reduction of COD versus PS:Fe(II) and PMS:Fe(II) (Fig. 1a). The control experiment was first setup without the addition of Fe(II) to investigate the possibility of PS and PMS in reducing the concentration of COD of pre-treated SLL. It was found that less than 3% of COD was reduced without the addition of Fe(II). The increasing Fe(II) concentration was found to enhance the percentage of COD reduction for the treatment of both systems. As shown in Fig. 1a, percentage of COD reduction was found to increase with increasing PS:Fe(II) and PMS:Fe(II) from 1:0.5 to 1:2. This result was due to the generation of the higher amount of SR and consequently, increased the COD reduction efficiency (Rastogi *et al.,* 2009). However, when the PS:Fe(II) and PMS:Fe(II) were increased to 1:3, no significant increment of COD reduction was observed. This result was attributed to the utilization of SR by the excess amount of Fe(II), as shown in Equation 4 (Matzek and Carter, 2016). In this situation, the rate of scavenging reaction of SR by Fe(II) (Eq. 4) is greater than the SR production rate (Eq. 2 and 3). Therefore, the SR formation was

limited by the excess amount of Fe(II) (Fagier *et al.,* 2016). At the ratio of 1:2, the maximum COD reduction was obtained with 22 and 20 % of COD reduction by PMS/Fe(II) and PS/Fe(II), respectively.
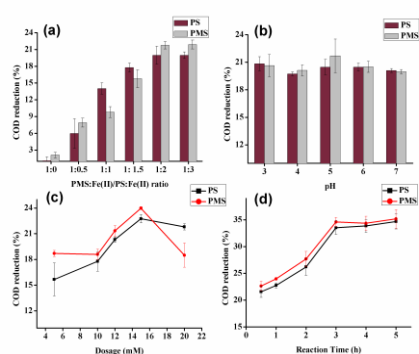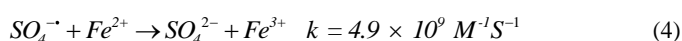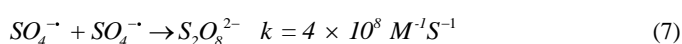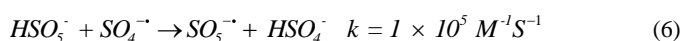
$$SO_4^{-\cdot} + Fe^{2+} \rightarrow SO_4^{2-} + Fe^{3+} \quad k = 4.9 \times 10^9 \ M^{-1}S^{-1} \quad (4)$$
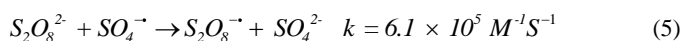

Fig. 1 The effect of (a) Oxidant:Fe(II) (dosage of oxidants = 12 mM, reaction time = 1 h, pH = 5, (b) pH (oxidant:Fe(II) = 1:2, dosage of oxidant = 12 mM (c) Oxidants dosage (oxidant:Fe(II) = 1:2, reaction time = 1 h, pH = 5 (d) Reaction time (oxidant:Fe(II) = 1:2, dosage of oxidants = 15 mM, pH = 5) on percentage COD reduction of pre-treated leachate.

The pH effect on the COD reduction efficiency was investigated from pH 3 to 7. The percentage of COD reduction was found to vary from 19.7 to 21.7 % for PMS and PS treatment systems, respectively (Fig. 1b). This result indicated that pH did not significantly influence the COD reduction. The data were found to be contradicted with some of the previous studies which indicated that the optimum organic pollutants removal efficiency occurred at acidic conditions due to acid-catalysis formation of SR (Zhang et al., 2015). This phenomenon is probably due to the complexation of dissolved organic pollutant with Fe(II) in landfill leachate. Organic-Fe(II) complexation can prevent the Fe(II) from been precipitated, thus enhanced the COD removal (Wu et al., 2014). Therefore, it could be an added advantage for this method to be coupled with coagulation-flocculation, which often lowering down the pH of the pre-treated landfill leachate. The optimum pH condition for SR-AOP was in the range of 4–5. Therefore, no additional pH adjustment is needed.

The effect of oxidant dosage concentration on COD reduction was investigated using PMS:Fe(II) and PS:Fe(II) of 1:2 and 1 h reaction time. The concentration of oxidants (PMS and PS) was varied from 5 mM to 20 mM (Fig. 1c). COD reduction efficiency was found to increase with increasing oxidant dosage from 5 to 15 mM. In PMS/Fe(II) and PS/Fe(II) system, the percentage COD reduction was increased from 18.7 % to 24 % and from 15.7 % to 22.8 %, respectively. The increased percentage of COD reduction was due to higher production of SR, which favored the oxidation process (Olmez-Hanci et al., 2013). However, the COD removal efficiency of both treatment systems was found to decrease after the oxidant dosage of 20 mM. This result was attributed to the scavenging reaction of SR by the excess amount of PS and PMS, as indicated in Eq. 5 and 6. The rate of SR production was much lower than the rate of scavenging reaction. In addition, peroxysulfate ($SO_5^{\cdot-}$) ($E^o = 1.1V$) and persulfate radical that ($S_2O_8^{\cdot-}$) ($E^o = 2.1V$) generated from the reaction are weaker oxidants in comparison with SR ($E^o = 2.5$-3.1 V), thus higher PS and PMS dosage could lower the COD reduction efficiency (Jaafarzadeh et al., 2016). Furthermore, SR may self-react and inhibit the COD reduction efficiency (Eq. 7) (Olmez-Hanci et al., 2013).

$$S_2O_8^{2-} + SO_4^{-\cdot} \rightarrow S_2O_8^{-\cdot} + SO_4^{2-} \quad k = 6.1 \times 10^5 \ M^{-1}S^{-1} \quad (5)$$

$$HSO_5^- + SO_4^{-\cdot} \rightarrow SO_5^{-\cdot} + HSO_4^- \quad k = 1 \times 10^5 \ M^{-1}S^{-1} \quad (6)$$

$$SO_4^{-\cdot} + SO_4^{-\cdot} \rightarrow S_2O_8^{2-} \quad k = 4 \times 10^8 \ M^{-1}S^{-1} \quad (7)$$

The effect of reaction times on the percentage of COD concentration was measured after 0.5, 1, 2, 3, and 5 h (Fig. 1d). After the first 3 h reaction, both PS/Fe(II) and PMS/Fe(II) systems showed significant COD reduction. The percentage of COD reduction for PS/Fe(II) and PMS/Fe(II) after 3 h of reaction time were 33.5 and 34.6 %. The efficiency of COD reduction was found to increase slowly to 34.7 and 35.2 % after 5 h for PS/Fe(II) and PMS/Fe(II), respectively. Hence, 3 h of reaction time was sufficient to achieve the highest efficiency in COD reduction of pre-treated SLL. At all reaction times, PMS/Fe(II) showed slightly higher COD removal as compared to PS/Fe(II). This condition might be due to the high reactivity of PMS as compared to PS in generating SR. As shown in the Eq. 6 and 7, PMS is 1000 times more reactive than PS.

Treatment of SLL using optimized SR-AOP

The efficiency of the combination of coagulation-flocculation with PMS/Fe(II) and PS/Fe(II) was re-evaluated using the previous optimized condition. The overall efficiency of the evaluated treatment methods is presented in Table 2. It has been observed that 83.9 and 84.8 % of COD were reduced from SLL by the combination of coagulation-flocculation treatment coupled with PS/Fe(II) and PMS/Fe(II), respectively. The final effluent was found to comply with the discharge standard, which is below 200 mg/L of COD.

Table 2 Summary of the performance of selected treatment process (Reaction condition: oxidant: Fe(II) ratio = 1:2, pH = 5.2, dosage = 12 mM, reaction time = 3 h).

Treatment	Parameters			
	COD ($\times 10^2$ mg/L) *(% Removal)*	TOC ($\times 10^2$ mg/L) *(% removal)*	Turbidity ($\times 10^2$ FAU) *(% removal)*	Colour ($\times 10^2$ Pt/Co) *(% removal)*
Raw Leachate	11.2 ± 0.2	3.47 ± 0.06	3.0 ± 0.1	50.98 ± 0.02
Coagulation-Flocculation (CF)	2.6 ± 0.1 *(76.8)*	0.95 ± 0.04 *(72.6)*	Not Detected *(100)*	3.1 ± 0.1 *(94)*
PMS- Fe(II)	1.7 ± 0.2 *(34.6)*	0.65 ± 0.02 *(31.5)*	-	Not detected *(100)*
PS- Fe(II)	1.8 ± 0.3 *(30.8)*	0.70 ± 0.03 *(26.3)*	-	-
Total Removal after CF + PMS- Fe(II)	*(84.8)*	*(81.8)*	-	-
Total Removal after CF + PS- Fe(II)	*(83.9)*	*(80.3)*	-	-

Ecotoxicity analysis

The changes in the ecotoxicity of SLL after coagulation-flocculation and SR-AOP treatments were investigated using zebrafish. The ecotoxicity of this study was assessed through the determination of LC_{50} for 48 h and 96 h (Table 3). LC_{50} is the concentrations of the chemical that exterminates 50 % of the test animals during the observation (OECD 2013). The toxic unit (TU) was calculated from the 96 h LC_{50} to determine the relative acute toxicity before and after treatment. 96 h LC_{50} and TU of raw leachate were 9.9 (% v/v) and 10.14, which are very toxic. The coagulation-flocculation pre-treatment reduced the acute toxicity of the SLL to only 1.74 TU. However, the TU of SLL was increased slightly to 3.13 and 1.84 after PMS/Fe(II) and PS/Fe(II) treatment. The increase of TU was attributed to the formation of sulfate ion after SR-AOP treatment. To prove this hypothesis, each of the treated SLL samples was analyzed using ion chromatography (Fig. 2). The result showed that after treated with SR-AOP, the concentration of sulfate ion increased to 5923 mg/L for PMS/Fe(II) and 4331 mg/L for PS/Fe(II). The sulfate ion is a common ion in nature. It is usually diluted in the water body rather quickly and non-bio cumulative. So far, the environmental standard for sulfate ion is rarely reported (WHO 2004). However, the higher level of sulfate concentration might be sensitive to some living organism such as for

zebrafish. In general, the treatment of pre-treated SLL using PS/Fe(II) shows higher potential application since it yields effluent with lower toxicity as compared to PMS/Fe(II)

Table 3 LC_{50} (% v/v) of SLL and treated SLL on zebrafish after 48 and 96 h exposure.

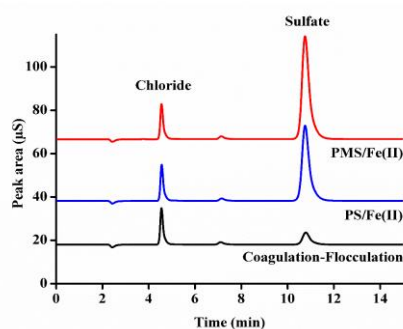| Treatment	48 h LC_{50}	96 h LC_{50}	Toxicity Unit (TU)
Raw Leachate	11.0 ± 0.2	9.9 ± 0.2	10.14 ± 0.02
Coagulation-Flocculation	58.7 ± 0.7	57.4 ± 0.7	1.74 ± 0.02
PS-Fe(II)	55.0 ± 0.5	54.3 ± 0.2	1.84 ± 0.02
PMS-Fe(II)	33.4 ± 0.3	32.0 ± 0.2	3.13 ± 0.03

Fig. 2 Chromatograms showing the distribution of anions in the treated SLL.

CONCLUSION

This study investigated the efficiency of SR-AOP in the treatment of pre-treated SLL. Almost 76.8 % of COD from SLL was removed after coagulation-flocculation pre-treatment. However, the treated SLL still required additional treatment since the COD concentration was exceeded the maximum discharge standard. It was found that the operating parameter in SR-AOPs treatment such as the ratio of PS and PMS to Fe(II), PS and PMS dosage, and reaction time had influence on the efficiency of COD removal. However, the pH did not show significant influence on the efficiency of COD reduction in SR-AOPs. By using the optimized condition, 30.8% and 34.6% of COD were effectively reduced using PS-Fe(II) and PMS-Fe(II), respectively. The COD concentration of SLL after SR-AOP treatment was lower than the standard discharge limit for most of the countries. This finding indicated that SR-AOPs treatment could be an alternative method to other conventional leachate treatment. In term of toxicity of effluent, the toxicity was increased slightly due to the presence of sulfate ion after SR-AOPs. The method for removal of sulfate ions such as ion exchange or chemical precipitation needs to be considered before practically applied the SR-AOPs in the real leachate treatment system.

ACKNOWLEDGEMENT

REFERENCES

Amor, C., E. De Torres-Socias, J. A. Peres, M. I. Maldonado, I. Oller, S. Malato, M. S. Lucas. 2015. Mature landfill leachate treatment by coagulation/flocculation combined with Fenton and solar photo-Fenton processes. *Journal of Hazardous Materials*, *286*:261-268.

Anipsitakis, G. P., D. D. Dionysiou, M. A. Gonzalez. 2006. Cobalt-mediated activation of peroxymonosulfate and sulfate radical attack on phenolic compounds. Implications of chloride ions. *Environmental Science & Technology, 4*0 (3):1000-1007.

American Public Health Association (APHA), American Water Works Association (AWWA), Water Pollution Control Federation, Water Environment Federation. 2012. *Standard methods for the examination of water and wastewater*, 22nd ed, American Public Health Association, Washington, DC.

Asaithambi, P., B. Sajjadi, A. R. A. Aziz, W. M. A.W. Daud. 2017. Ozone (O₃) and sono (US) based advanced oxidation processes for the removal of color, COD and determination of electrical energy from landfill leachate. *Separation and Purification Technology 172*:442-449.

Bashir, M. J. K., H. A. Aziz, S. S. A. Amr, S. Sethupathi, C. A. Ng, J. W. Lim. 2015. The competency of various applied strategies in treating tropical municipal landfill leachate. *Desalination and Water Treatment 54* (9):2382-2395.

Deng, Y., J. D. Englehardt. 2006. Treatment of landfill leachate by the Fenton process. *Water Research, 40* (20):3683-3694.

Deng, Y., R. Zhao. 2015. Advanced oxidation processes (AOPs) in wastewater treatment. *Current Pollution Reports, 1*(3):167-176.

Fagier, M. A., E. A. Ali, K. S. Tay, M. R. B. Abas. 2016. Mineralization of organic matter from vinasse using physicochemical treatment coupled with Fe2+-activated persulfate and peroxymonosulfate oxidation. *International Journal of Environmental Science and Technology 13*(4):1189-1194.

Ghanbari, F., M. Moradi. 2017. Application of peroxymonosulfate and its activation methods for degradation of environmental organic pollutants: Review. *Chemical Engineering Journal, 310* (1):41-62.

Ghanbari, F., M. Moradi, F. Gohari. 2016. Degradation of 2,4,6-trichlorophenol in aqueous solutions using peroxymonosulfate/ activated carbon/UV process via sulfate and hydroxyl radicals. *Journal of Water Process Engineering*, 9:22-28.

Hassan, M., Y. Zhao, and B. Xie. 2016. "Employing TiO₂ photocatalysis to deal with landfill leachate: Current status and development." Chemical Engineering Journal 285:264-275.

Hollert, H., S. H. Keiter. 2015. *Danio rerio* as a model in aquatic toxicology and sediment research. *Environmental Science Pollution Research*, 22 (21):16243-16246.

Hoornweg, D., P. Bhada-Tata. 2012. What a waste: A global review of solid waste management. Retrieved from https://openknow ledge. worldbank.org/handle/10986/17388

Jaafarzadeh, N., M. Omidinasab, F. Ghanbari. 2016. Combined electrocoagulation and UV-based sulfate radical oxidation processes for treatment of pulp and paper wastewater. *Process Safety and Environmental Protection*, 102:462-472.

Jung, C., Y. Deng, R. Zhao, K. Torrens. 2017. Chemical oxidation for mitigation of UV-quenching substances (UVQS) from municipal landfill leachate: Fenton versus ozonation. *Water Research*, 108:260-270.

Kurniawan, T. A., W. H. Lo, G. Y. Chan. 2006. Physico-chemical treatments for removal of recalcitrant contaminants from landfill leachate. *Journal of Hazardours Materials*, 129 (1-3):80-100.

Liu, Z., P. Zhan, F. Nie. 2016. Advanced treatment of leachate secondary effluent by a combined process of MFPFS coagulation and sulfate radical oxidation. *Polish Journal of Environmental Studies, 25*(4):1615-1622.

Matzek, L. W., K. E. Carter. 2016. Activated persulfate for organic chemical degradation: A review. *Chemosphere, 151*:178-188.

Moşneang, C. L., A. Grozea, I. Oprescu, E. Dumitrescu, F. Muselin, D. Gál, R. T. Cristina. 2014. Assessment of 2, 4-difluoroaniline aquatic toxicity using a zebrafish (*Danio rerio*) model. *The Thai Journal of Veterinary Medicine 44* (4):445-452.

OECD, Organisation for Economic Co-operation and Development. 2013. *Guidelines for the testing of chemicals, fish, early-life stage toxicity test*. OECD, Paris.

Olmez-Hanci, T., I. Arslan-Alaton, B. Genc. 2013. Bisphenol A treatment by the hot persulfate process: oxidation products and acute toxicity. *Journal of Hazardous Materials 263*, (2):283-90.

Rastogi, A., S. R. Al-Abed, D. D. Dionysiou. 2009. Sulfate radical-based ferrous–peroxymonosulfate oxidative system for PCBs degradation in aqueous and sediment systems. *Applied Catalysis B: Environmental 85*, (3-4):171-179.

Trebouet, D., J. P. Schlumpf, P. Jaouen, F. Quemeneur. 2001. Stabilized landfill leachate treatment by combined physicochemical–nanofiltration processes. *Water Research, 35*(12):2935-2942.

Westwood, D. 2007. *The determination of chemical oxygen demand in waters and effluents*. Environment Agency, National Laboratory Service, UK.

WHO, World Health Organization. 2004. *Guidelines for drinking-water quality: recommendations*. Vol. 1. World Health Organization, Geneva.

Wu, Xiaoliang, X. Gu, S. Lu, M. Xu, X. Zang, Z. Miao, Z. Qiu, Q. Sui. 2014. Degradation of trichloroethylene in aqueous solution by persulfate activated with citric acid chelated ferrous ion. *Chemical Engineering Journal*, 255:585-592.

Zhang, Q., J. Chen, C. Dai, Y. Zhang, and X. Zhou. 2015. "Degradation of carbamazepine and toxicity evaluation using the UV/persulfate process in aqueous solution. *Journal of Chemical Technology & Biotechnology*, *90* (4):701-708.

Zhou, D., H. Zhang, and L. Chen. 2015. Sulfur-replaced Fenton systems: Can sulfate radical substitute hydroxyl radical for advanced oxidation technologies? *Journal of Chemical Technology & Biotechnology*, *90* (5):775-779.