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Assessment of aeration pond operation in a constructed wetland receiving high nitrogen content wastewater from livestock area

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ABSTRACT

This study was performed to assess the operation conditions in the aeration pond (AP) of the surface flow constructed wetland (CW). The AP was employed to provide oxygen supply to the CW at alternating 3 h on and off. Batch test and prototype lab-scale test experiments were conducted in the laboratory to determine oxygen transfer coefficient (K_La) and oxygen consumption rate ($q_{O2}C_X$) values using samples from the AP. Field test monitoring was also performed to determine the water quality changes in the AP. Based on the field test monitoring, the effluent DO from the AP was increased by almost 20% due to the aeration. The $K_La_{(20°C)}$ and $q_{O2}C_X$ values obtained from the field tests were relatively higher in comparison with the values reported from other wastewater treatment technologies signified an increase in oxygen transfer in the AP. Findings showed that the AP is operating with high K_La and low $q_{O2}C_X$ which resulted to high cost in aeration system operation. Consequently, it is suggested that non-aeration time could be increased more than the aeration operation time of 3 h.

Keywords: Aeration time; Constructed wetland; Livestock wastewater; Oxygen consumption rate; Oxygen transfer coefficient

1. Introduction

Oxygen supply or aeration plays an important role in biological wastewater treatment process. In some cases, constructed wetland (CW) is designed with an aeration pond (AP) capable to perform biological treatment. Oxygen transfer rate (OTR) and oxygen uptake rate (OUR) have significant impacts on the design, optimal operation, and modeling of CWs [1]. Kadlec and Wallace [2] described three ways to transfer oxygen to wetlands: first is by direct transfer from the air at the contact surface of water and atmosphere, second is by plant-mediated transfer from leaves and stems to underground biomass, and lastly, oxygen dissolved in influent water. Oxygen concentration is usually undetected or present in very low concentrations in wastewater and thus, the oxygen input by the influent is generally negligible and lower than direct transfer from air and plant-mediated transfer [1]. Oxygen transfer process is considered as the primary consumer of electrical energy in the secondary treatment process and represents a significant capital cost as well [3]. The measurement and control of oxygen in biological processes allowed optimization of the aeration–mixing couple which has an important economic impact on energy savings [4]. Therefore, significant attention has been paid to the design and operation of aeration systems with lower capital cost and higher aeration efficiency in the wastewater treatment processes [3].

The OTR is influenced by several factors mentioned by Stenstrom and Gilbert [5] which include air flow rate, bubble diameter, temperature, viscosity, basin geometry (affects contact time between gas and liquid), wastewater composition (e.g., salts, surfactants, and biomass). The OUR is one of the fundamental physiological characteristics of culture growth

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and has been used for optimizing the fermentation process [6]. A number of methods have been developed to determine the OTR and OUR in bioreactors [7]. Extensive literatures on the OTR in bioreactors are available, and a considerable part of it has been published in the last year [8–11]. Substantial results on different aspects of oxygen transport have been reviewed in different works [12–18].

The CW in this study treats the wastewater effluents from livestock wastewater treatment plant, which is still highly polluted wastewater. Especially, the wastewater is containing high nutrient concentrations of nitrogen and phosphorus. The AP was incorporated in the surface flow (SF) CW system to improve the nutrient removal efficiency. Generally, SF CWs have variable oxygen levels depending on atmospheric diffusion, wind action, and the amount of algae or macrophytes available to introduce oxygen to the system. DO levels are highest at the air/water interface and decrease with depth. Depending upon the depth of the water and its quiescence, DO levels may be quite low at the bottom of the water column and even anaerobic just a few millimeters below the water/sediment interface [19]. Therefore, a coarse bubble diffuser system in the AP was installed to provide bubble aeration for biological treatment.

In this study, the oxygen transfer coefficient (K_La) and oxygen consumption rate ($q_{O2}C_X$) by the biomass have been determined to evaluate the OTR and OUR, and finally to assess the operation conditions in the AP. It is of great importance to characterize the efficiency of aerators in order to establish the optimal operating conditions, that is, ensure a maximum mass transfer of oxygen from the gas phase to the liquid phase. Therefore, the results could be useful to determine the ideal operating conditions in the AP.

2. Materials and methods

2.1. Description of the aeration pond

The SF CW located in the Geum River watershed in Korea was consisted of six cells including sedimentation ponds, deep and shallow marshes, and an AP using coarse bubble diffuser system (Fig. 1). The influent entering the CW is contaminated with high nutrient concentrations of nitrogen and phosphorus coming from piggery wastewater treatment plant and stormwater runoff generated from the contributing catchment area. The AP has a total surface area of 776 m^2, a total storage volume of 565 m^3, and an average depth of 0.73 m. The design hydraulic retention time (HRT) of treating wastewater from the inlet to the outlet in the AP is approximately 6.8 h. The AP was planted with *Phragmites australis* surrounding the water zone. *Phragmites australis* occupied area ranging from 43 to 95 m^2 with the lowest coverage during April and largest coverage on July. Normally, the oxygen supply in the AP is controlled with operating time of alternating on and off every 3 h.

Fig. 1. Aeration pond during oxygen supply time.

2.2. OTR and OUR determination method

The transport of oxygen and its consumption were not usually described together, and often measured by different methods in the past. Recently, it is usual to obtain both experimental values using the same technique, that is, simultaneous determination of both OTR and OUR in the same experiment [6,18]. Fig. 2 shows the diagram of the procedures performed for the determination of OTR and OUR. The mass balance for the dissolved oxygen in the assumed well-mixed liquid phase is shown in Eq. (1). The OTR is proportional to the concentration gradient, being the oxygen mass transfer coefficient, K_La.

$$\frac{dC}{dt} = \text{OTR} - \text{OUR} = K_La\left(C_S - C\right) - q_{O2}C_X \tag{1}$$

where dC/dt is the rate of oxygen accumulation in the liquid phase, OTR represents the oxygen transfer rate from gas to liquid phase, and OUR is the oxygen uptake rate by microorganisms. C_S is the DO concentration at initial time (mg/L) and C is DO concentration during the test (mg/L). The last term expressed by the product $q_{O2}C_X$, q_{O2} being the specific OUR of the microorganism employed and C_X being the biomass concentration.

Increasing temperatures may result to lower oxygen solubility, which leads to a smaller driving force ($C_S - C$) and hence, to a lower OTR. However, the diffusion rate of oxygen increases with increasing temperatures while the liquid viscosity and surface tension decrease. These effects result in an increased K_La value that might offset the smaller driving force [20]. The calculated K_La was corrected to K_La_{20} which was given for standard conditions, 1 atm of pressure and 20°C, by using Eq. (2):

$$K_La_{20} = K_La_T(\theta)^{20-T} \tag{2}$$

The theta factor (θ) was used to adjust the volumetric mass transfer coefficient at non-standard water temperature. Generally, the accepted value of the temperature correction factor is 1.024 [5].

The dynamic method was used, where dissolved air is transported into the liquid by molecular diffusion. The mass balance equation of oxygen was shown in Eq. (1). Eq. (1) was evaluated in Eq. (3):

$$\frac{dC}{dt} + q_{O2}C_X = K_La \cdot C_S - K_La \cdot C \tag{3}$$

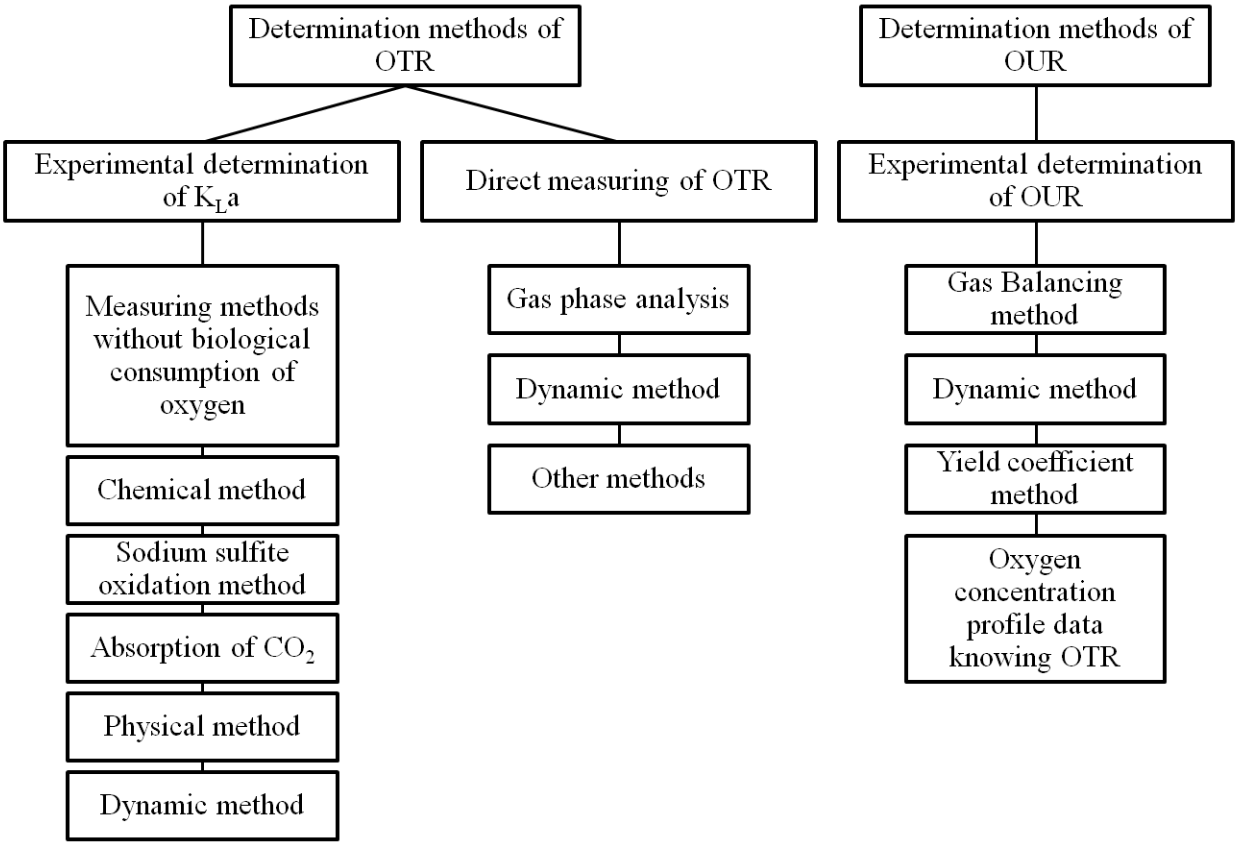

Fig. 2. Determination methods of OTR and OUR.

In addition, when OUR is zero ($q_{O2}C_X = 0$), K_La can be calculated using Eq. (4):

$$\frac{dC}{dt} = K_La\left(C_S - C\right) \quad (4)$$

Eq. (3) was evaluated in Eq. (5):

$$C = C_S = \left(C_S - C_0\right)e^{-K_La\cdot t} \quad (5)$$

where C_0 is the initial condition. Evaluating the log of Eq. (5) results in Eq. (6):

$$\ln\left|C_S - C\right| = \ln\left|C_S - C_0\right| - K_La\cdot t = \text{constant} - K_La\cdot t \quad (6)$$

The dynamic method of Taguchi and Humphrey [21] enables the determination of the transfer coefficient during the course of fermentation, as well as the quantity of oxygen consumed by the microorganisms. A profile of DO concentration from Eq. (1) during a cycle of turning aeration off and on is shown in Fig. 3.

During the fermentation, wherein the aeration is stopped, the consumption is no more compensated and C decreases with time, due to the consumption by the bacteria, which are also increasing in number according to Eq. (7):

$$\frac{dC}{dt} = -q_{O2}C_X \quad (7)$$

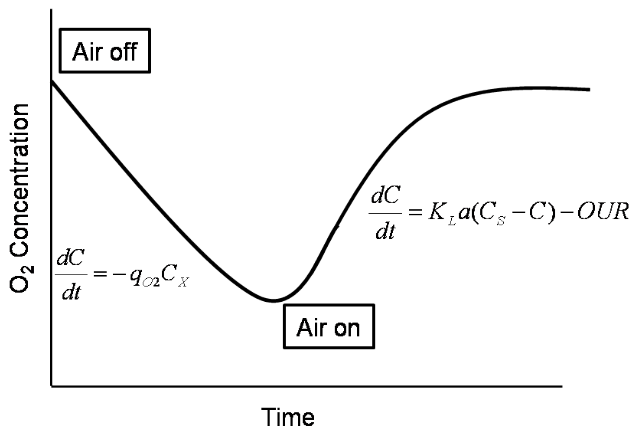

Fig. 3. Simulation of response of DO for dynamic measurement of OUR and K_La during fermentation.

Integrating Eq. (1) with the initial condition $t = 0$, $C = C_S$, gives:

$$\left(C_S - C\right) = q_{O2}C_X\cdot t \quad (8)$$

Plotting (C_S – C) vs. time gives a straight line of slope $q_{O2}C_X$.

2.3. Experimental procedure

Two different experiments in the laboratory were performed to investigate the characteristics of wastewater in terms of OTR and OUR. The first experiment was conducted in a batch reactor (volume: 1 L), while the second experiment was a prototype lab-scale reactor of the AP operated with continuous flowing of the AP influent (volume: 10.9 L, HRT: 6.8 h). The water samples used in the batch reactor were collected at the inlet, outlet, and middle region of the AP in the CW. The oxygen supply in the prototype lab-scale reactor was operating during 3 h and stopped every 3 h. In both experiments, the DO concentrations were measured at the middle point of the reactor by a portable DO meter probe. In addition to the laboratory experiment tests, field tests were also performed to determine the actual OTR and OUR in the AP. DO concentrations at the inlet, outlet, and middle region of the AP in the CW were measured at 10 min interval during 7 h in six dry events. The K_La and $q_{O2}C_X$ values were calculated using the data obtained from the laboratory and field test experiments.

2.4. Water quality monitoring and data analysis

The water quality samples were collected at the inlet and outlet of the AP in the CW from October 2008 to August 2014. Parameters such as DO, pH, and temperature were measured on site using portable meters. Samples were transported to the laboratory for the chemical analyses (biological oxygen demand [BOD], total nitrogen [TN], total Kjeldahl nitrogen [TKN], ammonium nitrogen [NH_4-N], nitrate [NO_3-N], total phosphorus [TP], and phosphate [PO_4-P]). SYSTAT 9.0 and OriginPro 8 software packages were used for the analysis of variance (one-way ANOVA) and plotting of data.

3. Results and discussions

3.1. Water quality characteristics in the aeration pond

The influent and effluent water quality characteristics at the AP in the CW are summarized in Table 1. The concentration of most water quality parameters increased except for BOD, NH_4-N, and NO_3-N in the AP due to growing microorganisms enhanced by oxygen supply. The occurrence of both aeration and low oxygen conditions suggests that the nitrification and denitrification processes could occur simultaneously in the AP, which resulted to the decrease of both NH_4-N and NO_3-N. The changes in DO and pH were relative; an increase in DO corresponds to an increase in pH. Zhu and Silora [22] pointed out that no obvious nitrification could be observed when DO concentration is lower than 0.5 mg/L. According to Vymazal [23], approximately 4.3 mg O_2 per mg of ammoniacal nitrogen oxidized to nitrate nitrogen is needed. Paul and Clark [24], and Cooper

Table 1
Summary of the influent and effluent concentrations in the AP

Parameter (unit)	Influent			Effluent		
	Minimum	Maximum	Mean ± SD	Minimum	Maximum	Mean ± SD
Temperature (°C)	4.1	29.8	19.8 ± 7.9	7.0	31.2	21.5 ± 8.9
pH	7.0	9.9	8.1 ± 0.6	7.7	10.0	8.5 ± 0.7
DO (mg/L)	0.3	7.4	3.5 ± 2.2	0.3	6.5	4.1 ± 2.3
BOD (mg/L)	15.4	115.2	42.8 ± 24.8	24.1	79.2	38.7 ± 18.5
TN (mg/L)	77.0	206.8	141.9 ± 39.3	88.7	212.5	177.0 ± 43.1[a]
TKN (mg/L)	52.4	146.6	89.8 ± 26.7	68.0	137.5	115.6 ± 23.7[a]
NH_4-N (mg/L)	52.3	87.2	69.6 ± 11.7	52.0	82.6	67.4 ± 10.0
NO_3-N (mg/L)	3.5	16.0	10.1 ± 2.5	7.9	11.6	9.7 ± 1.6
TP (mg/L)	1.6	11.0	5.1 ± 2.1	2.5	10.4	5.9 ± 2.8
PO_4-P (mg/L)	0.1	4.3	1.4 ± 0.8	0.5	4.1	1.9 ± 1.2

[a]Significant difference with respect to influent concentration ($p < 0.05$).

Table 2
K_La and $q_{O2}C_X$ values for the batch reactor and prototype lab-scale reactor tests

Parameter		Batch reactor test (n = 3)			Lab-scale reactor test (n = 3)	
		Influent	Middle	Effluent	First aeration	Second aeration
K_La	T_0 (°C)	20.3	20.8	21.6	20.0	20.1
	DO_0 (mg/L)	2.27	2.26	3.85	3.15	3.31
	$K_La_{(T°C)}$ (h^{-1})	10.84	12.22	13.28	1.33	1.28
	$K_La_{(20°C)}$ (h^{-1})	10.82	12.0	12.84	1.22	1.29
$q_{O2}C_X$	T_0 (°C)	20.4	20.9	21.7	20.1	19.8
	DO_0 (mg/L)	6.71	7.18	7.73	4.72	4.58
	$q_{O2}C_X$ (mg O_2/L·h)	5.69	8.56	7.64	0.82	0.83

et al. [25] reported that optimum pH values for nitrification and denitrification may vary from 6.6 to 8.0 and from 6 to 8, respectively. However, acclimatized systems can be operated to nitrify at a much lower pH value. Temperature is low at the inlet and it was observed that the temperature was between 4°C and 30°C. The optimum temperature for nitrification in pure cultures ranges between 25°C and 35°C, and in soils, between 30°C and 40°C. Denitrification strongly depends on temperature. Rates of denitrification increase up to a maximum in the region of 60°C–75°C and then decline rapidly above this temperature [24,26].

Table 3
Oxygen consumption rate for field test (n = 6)

Sampling point in the AP		T_0 (°C)	DO_0 (mg/L)	$q_{O2}C_X$ (mg O_2/L·h)
Inlet	Mean	23.8	1.91	0.43
	Range	17.5–28.2	0.32–3.06	0.08–0.07
Middle region	Mean	24.9	2.97	1.14
	Range	17.3–32.7	0.73–4.48	0.38–2.12
Outlet	Mean	23.5	3.41	0.64
	Range	17.2–28.5	0.96–5.11	0.37–0.90

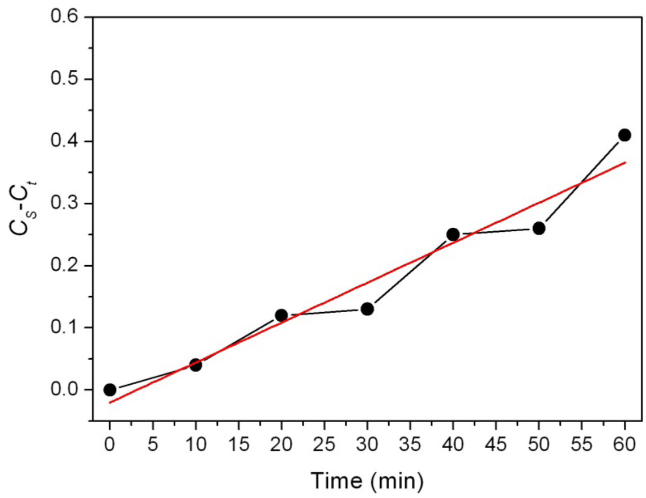

Fig. 4. Variation of $C_S - C_t$ with respect to time for field test during fermentation (date: 07/22/2011, sampling point in the AP: middle region, DO_0: 0.73 mg/L, T_0: 28.6°C).

3.2. Characteristics of wastewater from the laboratory experiments

The results of the batch reactor and prototype lab-scale reactor experiments are presented in Table 2. The mean $K_La_{(T°C)}$ and $q_{O2}C_X$ values of the different water samples in a batch reactor test were ranging from 10.84 to 13.28 h^{-1} and 5.69 to 8.56 mg O_2/L h, respectively; while the values of the prototype lab-scale reactor test were 1.28–1.33 h^{-1} and 0.82–0.83 mg O_2/L h, respectively. Comparing the results of the batch reactor and prototype lab-scale reactor test, the K_La and $q_{O2}C_X$ values were approximately 10 times lower for the prototype lab-scale reactor indicating a significant difference ($p < 0.001$). The K_La values were presumed to be affected by different environmental factors, such as temperature. Based on Table 2, the $K_La_{(20°C)}$ values were lower or higher than $K_La_{(T°C)}$ values which ranges between 10.82 and 12.84 h^{-1} for batch reactor test and 1.22 and 1.29 h^{-1} for the prototype lab-scale test.

3.3. OTR and OUR by field test

$q_{O2}C_X$ values from the field test data are summarized in Table 3.. On the other hand, $q_{O2}C_X$ calculation vs. time diagram is exhibited in Fig. 4. When the aeration was stopped in AP, DO concentrations were measured during fermentation. The $q_{O2}C_X$ values were equal to the slope, and numerically between 0.08 and 2.12 mg O_2/L h. The mean $q_{O2}C_X$ values in the inlet, middle region, and outlet points were observed to be 0.43, 1.14 and 0.64 mg O_2 /L h, respectively. Statistical analysis showed that the $q_{O2}C_X$ values from the field test were significantly different with the batch reactor test ($p < 0.001$), but not significant with the prototype lab-scale reactor test ($p > 0.05$). During the fermentation, wherein the aeration is stopped, the consumption is no more compensated and DO concentration decreases with time, due to the consumption by the bacteria. When the aeration was turned on again, the DO concentration increased until it reached a steady-state concentration. In this condition both the OTR and OUR terms apply [6].

Table 4 shows the K_La values using two different conditions (that is, with or without $q_{O2}C_X$) with the initial water temperature and DO concentrations. The curve

Table 4
Oxygen transfer coefficient for field test (n = 6)

Sampling point in the AP		T_0 (°C)	DO_0 (mg/L)	$q_{O2}C_X \neq 0$		$q_{O2}C_X = 0$	
				$K_La_{(T°C)}$ (h^{-1})	$K_La_{(20°C)}$ (h^{-1})	$K_La_{(T°C)}$ (h^{-1})	$K_La_{(20°C)}$ (h^{-1})
Inlet	Mean	22.7	1.32	4.91	4.60	1.27	1.19
	Range	16.8–28.9	0.25–2.23	2.84–6.16	2.43–6.38	0.71–1.94	0.76–1.78
Middle region	Mean	23.1	1.80	5.24	4.87	1.71	1.60
	Range	16.5–28.8	0.40–3.74	2.76–6.82	2.62–7.40	1.27–1.99	1.17–1.82
Outlet	Mean	22.9	1.99	5.83	5.44	1.77	1.66
	Range	16.7–28.7	0.31–3.56	3.64–9.81	2.96–8.96	1.35–2.08	1.30–2.09

presented in Fig. 5 shows the profiles of the K_La values from Eq. (6). The K_La values observed ranges from 0.71 to 2.08 h^{-1} when excluding the OUR calculation ($q_{O2}C_X = 0$) and from 2.76 to 9.81 h^{-1} when including the OUR calculation ($q_{O2}C_X \neq 0$), respectively. The mean K_La values in the inlet, middle region, and outlet with OUR calculation were 3–4 times higher than those without OUR calculation. Statistical analysis showed that the difference between two calculations was significant ($p < 0.001$). The determination of K_La of the setup helps in experimentally evaluating oxygen transfer capacities of the bioreactor [4]. The result having high K_La values gives positive effect on the OTR.

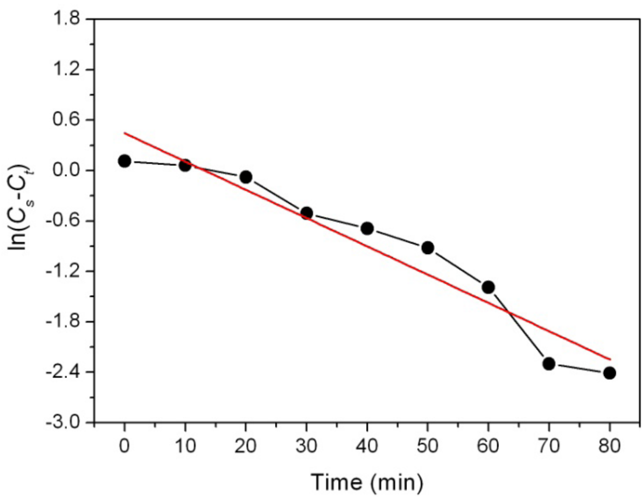

Fig. 5. Variation of $\ln(C_S - C_t)$ with respect to time for field test (date: 07/22/2011, sampling point in the AP: outlet, DO_0: 0.31 mg/L, T_0: 28.7°C).

3.4. Operation time at the aeration pond

The comparison of K_La values available in the literature with the values obtained in this study was shown in Table 5. The standardized $K_La_{(20°C)}$ of 10.82–12.84 h^{-1} obtained from the batch reactor test was comparable with those of the studies conducted by Tyroller et al. [1], Banks et al. [29], and Rainwater and Holley [30] in their laboratory study (0.01–0.21 h^{-1}) and outdoor experiments (0.013–0.132 h^{-1}), and approach the values obtained in stagnant open water. The $K_La_{(20°C)}$ values (1.22–1.29 h^{-1}) in the prototype lab-scale reactor test were comparable with those obtained by Foree [27], Rathbun et al. [28], and Rainwater and Holley [30] from the laboratory study of slow-running waters. It was observed that the $K_La_{(20°C)}$ values in this study were higher than other studies. The $K_La_{(20°C)}$ values obtained from the field tests range between 0.76 and 8.96 h^{-1}, which was relatively high in comparison with the values reported from other wastewater treatment technologies because of the AP that increased the oxygen transfer. On the other hand, the $q_{O2}C_X$ values obtained from the field tests were between 0.08 and 2.12 mg O_2/L h. Zamouche et al. [4] indicated that $q_{O2}C_X$ values of clear water ranges from 0.67 to 3.01 mg O_2/L h in the batch reactor. Based on the findings, the high K_La and low $q_{O2}C_X$ values obtained in this study signify that the AP is supplying excessive oxygen which resulted to high cost in aeration system operation. Consequently, the operation

Table 5
Comparison of K_La values available in the literature with values obtained in this study

Reference	K_La (h^{-1})	Experimental conditions
[27]	0.015–0.97	Reaeration in small streams with various flow characteristics; determination of K_La with the radioactive tracer krypton-85 and tritium at a temperature of 25°C
[28]	0.28–0.42	Laboratory study on a small water tank, determination of K_La with ethylene and propane as tracers; test on different mixing conditions and effect of surfactants at a temperature of 25°C
[29]	0.023–0.036	Laboratory study on a small water tank to evaluate the effect of artificial rain on the oxygen concentration; K_La was calculated for a temperature of 20°C
[30]	0.49–0.72	Laboratory study using a water tank to evaluate the effect of temperature and soil adsorption on the tracer method; K_La was calculated for a temperature of 20°C
[31]	0.063 and 0.11	Oxygen transfer in a lake, considering a water column as representative for lake conditions; estimation of reaeration coefficient by a mass balance on oxygen; K_La was calculated for a temperature of 20°C
[32]	0.33–10.6	Field study on reaeration on sewers by applying a tracer method with sulphur hexafluoride as tracer gas
[1]	0.01–0.21	Laboratory study on the OTR in an unplanted gravel bed with varying HRT; K_La was normalized for a temperature of 20°C
[1]	0.013–0.132	Outdoor experiment on the OTR in a HSSF CW at HRTs of 15 and 45 h
[33]	0.15–1.67	Laboratory study on a wastewater bench-scale ultra-filtration membrane bioreactor using pure oxygen; K_La was calculated with different MLSS concentrations and normalized for a temperature of 20°C
This study	10.82–12.84	Laboratory study on a batch reactor with various wastewaters by applying a dynamic method; K_La was normalized for a temperature of 20°C
This study	1.22–1.29	Laboratory study using the lab-scale reactor of the aeration pond in the CW by applying a dynamic method; K_La was normalized for a temperature of 20°C
This study	0.76–8.96	Field study in the aeration pond of the CW by applying a dynamic method; K_La was normalized for a temperature of 20°C

time of the AP must be changed to reduce the energy cost. For a more economical operation of AP, it is suggested to increase the non-aeration time more than the aeration operation time of 3 h.

4. Conclusions

This study assessed the operation time in the AP of the SF CW receiving high nitrogen content wastewater and the suggestion of the CW operation by performing experiments to determine the K_La and $q_{O2}C_X$ values. The CW is designed with AP capable of treating the high nutrient concentration wastewater effluents from livestock wastewater treatment plant. The treatment performance of the AP in the CW showed that most of the water quality parameters increased except for BOD, NH_4-N, and NO_3-N in the AP due to growing microorganisms caused by the oxygen supply. The availability of oxygen supply in the AP was alternating on and off every 3 h. The results of the K_La showed that the mean standardized $K_La_{(20°C)}$ obtained from the batch reactor test were significantly greater than the values of the prototype lab-scale reactor test. The $K_La_{(20°C)}$ values obtained from the field tests were relatively high in comparison with the values reported from other wastewater treatment technologies signifying that the aeration has increased the oxygen transfer in the AP. The $q_{O2}C_X$ values obtained from the two different experiments in the laboratory and field tests were significantly low. Based on the findings, the AP is operating with high K_La and low $q_{O2}C_X$, which resulted to high cost in aeration system operation. Therefore, it is suggested that for a more economical operation of an AP, the non-aeration time could be increased more than the aeration operation time of 3 h. The results of this study may be used to determine the economical aeration time for optimum efficiency of the CWs.

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