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The optimum substrate to biomass ratio to reduce net biomass yields and inert compounds in biological leachate treatment under pure-oxygen conditions

K. J. Chae, S. E. Oh, S. T. Lee, J. W. Bae, In S. Kim

Abstract To investigate the effect of both initially present soluble inert COD (S_I) and soluble inert COD formed by microbial activities (S_{PM}) on the effluent soluble residual COD (S_R) and to determine biokinetic constants, the pure-oxygen was employed for the batch assays of biological leachate treatment. The results of this work showed that the effluent residual soluble COD was entirely composed of S_I and S_{PM}, therefore, could not be reduced below 7–10% of total influent soluble COD ($S_{T0.inf}$), corresponding to the organics removal efficiency of 93–90%. The value of S_I of leachate, which is associated with the types of wastewaters, was determined as approximately 7.84% of $S_{T0.inf}$, and the soluble inert COD by microbial activities was assessed by means of the coefficient f_{PM} of 0.0474. These results mean that significant amount of feed leachate COD may pass the biological system without any change. On the basis of the concept that microorganisms must satisfy their maintenance energy requirements prior to synthesizing new biomass, a set of batch assays with various ratios of $S_{T0.inf}/X_0$ were carried out to evaluate their effects on the excess biomass production. Decreasing the supply of substrate per unit biomass resulted in gradual decrease in the biomass yields, but, at the same time, it resulted in gradual increase in the bacteria mediated inert COD as a side effect. The optimum ratios of $S_{T0.inf}/X_0$ were concluded as 0.2–0.6 according to the careful consideration of both aspects on the reduction of net sludge yields and inert COD from microbial activities.

List of symbols

Y_S	biomass yield coefficient (mg mg^{-1})
Y_G	maximum biomass yield coefficient (mg mg^{-1})
q_m	specific substrate uptake related to maintenance energy requirements (mg mg^{-1} h^{-1})
μ	specific growth rate (mg mg^{-1} d^{-1})
μ_{max}	maximum growth rate (mg mg^{-1} d^{-1})
K_S	half saturation constant (mg l^{-1})
k	specific substrate utilization rate (d^{-1})
k_d	death rate coefficient (d^{-1})
r_S	rate of substrate uptake (mg l^{-1} d^{-1})
r_X	rate of biomass production (mg l^{-1} d^{-1})
S_{S0}	initial soluble readily biodegradable substrate (mg l^{-1})
S_{RS}	remaining S_{S0} (mg l^{-1})
S_S	soluble readily biodegradable substrate (mg l^{-1})
X_0	initial biomass concentration (mg l^{-1})
X	biomass concentration (mg l^{-1})
$S_{T0.inf}$	total influent soluble substrate (mg l^{-1})
$S_{T0.eff}$	total effluent soluble substrate (mg l^{-1})
S_I	initially present soluble inert compounds (mg l^{-1})
S_R	soluble residual compounds (mg l^{-1})
S_{PM}	soluble inert compounds produced by microbial activity (mg l^{-1})
f_I	fraction of S_I in $S_{T0.inf}$
f_{PM}	fraction of S_{PM} in S_{S0}
S_R leachate	residual soluble compounds of leachate (mg l^{-1})
S_{PM} glucose	soluble inert compounds by microbial activity as feed with glucose (mg l^{-1})
S_{PM} leachate	soluble inert compounds by microbial activity as feed with leachate (mg l^{-1})
$S_{t(n)}$	soluble substrate at time nth iteration in modeling (mg l^{-1})
$S_{R(t)}$	relative soluble substrate at time t (mg l^{-1})
$t_{1/2}$	time at half of initial soluble substrate utilized (h)
MLVSS	mixed liquor volatile suspended solids (mg l^{-1})
COD	chemical oxygen demand (mg l^{-1})

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1 Introduction

Landfill leachate is one of highly contaminated and heterogeneous wastewaters. Its composition and characteristics, in particular, strictly depend on factors such as waste types landfilled, climate, contents of organic matter, hydrogeological structure of the landfill, operational condition and age of landfill [3, 5, 11, 16]. Leachate often contains high concentrations of easily biodegradable and non-biodegradable organic matters as well as inorganic ions. Therefore, leachate could be detrimental to groundwater, river, lake, and soil if it is not properly collected and treated before discharge into receiving water body. At present, a number of treatment plants for landfill leachate are being operated and are under construction in Korea. As environmental regulations and requirements become more strict, the required BOD to discharge into receiving water for the landfill sites producing leachate more than 2000 ton d^{-1} was amended from 100 to 70 mg l^{-1} from July of 1999, in Korea. These strict effluent discharge standards from leachate treatment plant often require removal efficiencies of more than 92–96% for both BOD and COD. However, removal efficiencies above 92–96% of COD are quite difficult to meet and also require extremely careful evaluation of the process. The capabilities of the present treatment processes are quite limited due to the high contents of both initially present inert COD in influent and the inert COD produced by microbial activities. Sometimes, unacceptable discharge of landfill leachate treated by traditional biological processes has its origin in the over-estimation of COD removal efficiencies. Many researchers have studied the formation of inert compounds and the methods to reduce excess biomass yields in biological processes, separately [6, 8, 15, 17, 22]. However, in this study, two concepts were considered together to understand biological processes more appropriately.

Pure-oxygen aeration was introduced in this research to treat leachate, because it can provide the fast organics and nitrogen removals compared to conventional air-activated sludge processes, thus pure-oxygen process is strongly applicable to the on-site landfill leachate treatment plants having space restriction. The advantages of pure-oxygen process are; (1) capability to meet higher oxygen demands, (2) ability to maintain higher biomass concentrations in the aeration tank and thus provide equivalent treatment in a smaller-volume aeration tank, (3) improved sludge settleability, (4) lower net sludge yields per unit organics removed, (5) more stable treatment etc. [4, 13, 14]. In pure-oxygen processes, it may be expectable that the high biomass concentration decreases the sludge production by allocating substrate into satisfying maintenance energy requirements prior to providing the energy available for new cell synthesis. Consequently lots of operating costs can be saved. However, a number of contradictory results on benefits of pure-oxygen process exist in the literature [9, 10, 14]. In spite of these merits of the pure-oxygen process, few works have been performed to investigate the potential for on-site landfill leachate treatment in pure-oxygen supplemented system. Therefore, the objectives of this work were to study the effects of inert COD from initially present in influent and from microbial activities on the residual COD of effluent, biokinetic constants and modeling as well as the potential reduction of sludge yields as basic information for the application of pure-oxygen in on-site leachate treatment plants. Finally, the optimum organics vs. biomass ratios to reduce simultaneously both microorganism mediated inert compounds and excess biomass production were defined.

1.1 Inert COD formation by microbial activities

The substrate utilized by the bacterial cell in the wastewater treatment processes is used for the complex cellular functions, such as new cell synthesis, synthesis of intracellular storage compounds (readily re-assimilated during the absence of primary substrate), formation of exopolymers and cell maintenance [15, 18, 19, 23, 24]. In general, the net sludge production of a biological wastewater treatment plant decreases with increasing sludge age [15, 23]. This reduction in sludge generation can be explained by the numerous mechanisms such as cell maintenance energy requirements, internal and external decay of cells, endogenous respiration, predation by protozoa and cell lysis due to adverse environmental conditions. From these diverse microbial activities in the wastewater treatment processes, soluble inert (or refractory) organic compounds as microbial by-products are generated. Their intensities quite depend on the conditions of actual biological systems [6, 8, 17]. From the previously conducted research, it is common that internal decay(endogenous respiration) in the absence of primary substrate is due to the assimilation of intracellular storage compounds to maintain the cells. After internal decay, death-regeneration growth (or cryptic growth) occurs by decay of cells and subsequent consumption of the destroyed cell materials as a secondary substrate to synthesize new biomass [23]. Inert COD, formed through cell lysis, and external decay, is not metabolized under the actual conditions in activated sludge systems. Ince et al. (1998) observed some amount of inert soluble COD formation when a brewery wastewater was digested anaerobically. Furthermore, it was reported that residual microbial inert materials accounting for 6–7% of the initially present degradable COD were observed from the wastewater containing no initially inert fraction [17]. Figure 1 describes the substrate allocation and the origins of inert organic compounds in bacteria mediated wastewater treatments. In order to develop a model appropriately describing the processes, careful consideration of residual inert CODs from microbial metabolic activities and from influent wastewaters should be given.

1.2 Reduction of excess biomass production

The costs for the disposal of excess biomass produced in biological wastewater treatment processes may account for about 60% of total plant operating costs [7]. As shown in Fig. 1, microorganisms allocate the organic substrates into new biomass synthesis, cell maintenance and production of storage compounds and exopolymers. Pirt (1975) proposed a useful relationship in Eq. (1) for determining the allocation of the carbon source and energy source in a biological system [2, 15, 18]:

$$\frac{1}{Y_S} = \frac{q_m}{\mu} + \frac{1}{Y_G} \quad . \tag{1}$$

In principle, maintenance energy requirement is satisfied prior to providing the energy requirement for new cell synthesis. Therefore, it is quite reasonable that increasing the amount of substrate utilization for cell maintenance decreases the observed yield [15, 22]. Low et al. (1999) demonstrated that in continuously-fed microbial reactor, substrate limited, excess biomass production decreases proportionally to biomass concentration by diverting substrate into maintenance requirement prior to making energy for anabolism. By Low et al.'s explanation, the total consumption of energy source is equal to the sum of substrate utilized for cell maintenance function and anabolism:

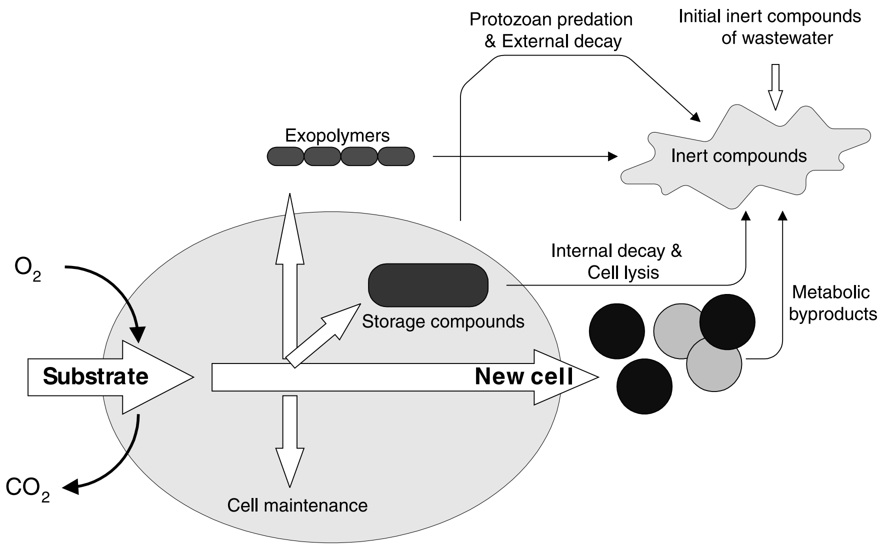

Fig. 1. Substrate flow and production of inert organic compounds in bacteria mediated wastewater treatment systems (modified from [19])

$$-r_S = -\frac{1}{Y_G} r_X - q_m X \quad , \tag{2}$$

and the biomass production rate and the substrate utilization rate for cell synthesis can be represented by Eqs. (3) and (4), respectively. If Y_G and q_m are constant and the biomass production is substrate limited, then the excess production of biomass may decrease proportionally with biomass concentration [15]:

$$r_X = Y_G(r_S - q_m X) \quad , \tag{3}$$

$$-r_{SG} = -\frac{1}{Y_G} r_X = -r_S + q_m X \quad . \tag{4}$$

1.3
Determination of soluble inert CODs from initially present in leachate and microbial activities

The total soluble COD concentration of feed leachate ($S_{T0.inf}$) is equal to the sum of the initially present inert soluble COD (S_I) which by-passes the treatment system without any change and the readily biodegradable soluble COD (S_{S0}) (Eq. (5)) [8]. S_I content of leachate gradually increases as a landfill stabilizes, therefore, S_I should be considered carefully to design the leachate treatment plant with respect to landfill ages:

$$S_{T0.inf} = S_{S0} + S_I \quad . \tag{5}$$

The soluble COD in the effluent from a bioprocess treating leachate includes not only biodegradable and non-biodegradable compounds from the raw leachate, but also biodegradable and non-biodegradable compounds produced by the microbial activities in the treatment system itself. Thus, the effluent soluble COD of a biological reactor ($S_{T0.eff}$) includes the remaining readily biodegradable influent soluble COD (S_{RS}), initial soluble inert COD in influent (S_I), and soluble inert COD from microbial activities (S_{PM}):

$$S_{T0.eff} = S_{RS} + S_I + S_{PM} \quad . \tag{6}$$

Experimental approaches, both comparison method and incremental method, were proposed to separately assess S_I and S_{PM} by Germirli et al. (1991) and Ince et al. (1998)[8].

1.4
Comparison method

Two batch reactors having the same initial COD are operated in parallel. One is fed with the leachate as a sole substrate, and the other with glucose. When the soluble COD in each reactor have declined to constant plateau value (the biodegradable substrate was almost entirely consumed), at this point the measured COD value is considered as a residual soluble COD (S_R) including both S_I and S_{PM}. The specific content of inert COD, such as hardly biodegradable cell wall debris, via protozoan predation is also included in S_{PM}, because its individual assessment is quite difficult. The value of S_{PM} can be determined with measuring the residual COD of glucose reactor, because glucose itself has no inert organic material. Then S_I content of the leachate is calculated as Eq. (7) on the assumption of Eq. (8):

$$S_I = S_{R\,leachate} - S_{PM\,glucose} \quad , \tag{7}$$

$$S_{PM\,leachate} \cong S_{PM\,glucose} \quad . \tag{8}$$

By the definitions, fraction of initial soluble inert COD fraction (f_I), and fraction of soluble inert COD formed by microbial activities (f_{PM}) are expressed as follows:

$$f_I = \frac{S_I}{S_{T0.inf}} \quad , \tag{9}$$

$$f_{PM} = \frac{S_R - S_I}{S_{T0.inf} - S_I} = \frac{S_{PM}}{S_{S0}} \quad . \tag{10}$$

If we assume that the complete removal of readily biodegradable compounds is achieved, the soluble residual COD (S_R) is identical to the sum of soluble inert organics originating both from the leachate and from microbial activities (Eq. (11)) and expressed again as Eq. (12) by combining Eq. (11) with Eqs. (5) and (8):

$$S_R = S_{PM} + S_I \quad , \tag{11}$$

$$S_R = f_{PM} S_{T0.inf} + (1 - f_{PM}) S_I \quad . \tag{12}$$

2 Experimental set-up

2.1 Raw leachate characteristics

The composition of a landfill leachate determines its relative treatability and configuration of the treatment process. Its exact understanding, therefore, should be conducted in preference to the process design. The raw leachate for a series of batch experiments was collected from Unjung landfill site in Kwangju, Korea, and delivered to the lab in a bottle and stored at 4 °C for whole period of experiments. All analyses were performed according to Standard Methods [1]. As shown in Table 1, the raw leachate contains high concentration of ammonia nitrogen and organics as well as ions such as Cl^-, Na^+, K^+ and Mg^{2+}. However, the contents of heavy metals are relatively low.

Table 1. Characteristics of raw leachate

Constituents	Conc. (mg l^{-1})	Constituents	Conc. (mg l^{-1})
pH	6.92	Chloride	3,658
COD	16,200	Cd	N.D.
BOD_5	11,700	Cr	0.24
TOC	7,305	Pb	0.09
TSS	3,686	Zn	0.30
Ammonia-N	1,758	Cu	1.70
TKN	1,831	Ni	N.D.
Nitrite	0.80	Sulfate	675
Nitrate	2.80	Sodium	1,922
Total-P	13.10	Magnesium	240
Ortho-P	11.08	Potassium	1,182
Alkalinity as $CaCO_3$	6,430	Calcium	415

N.D.: not detectable

2.2 Pure-oxygen Master Culture Reactor (MCR)

Seed microorganisms for the experiments were obtained from an enriched steady-state pure-oxygen Master Culture Reactor (MCR), its operating protocol was developed by Young and Tabak (1993), which supplies constant and stable microorganisms at any time (Fig. 2). Oxygen concentration in MCR was maintained of about 8 ± 1.0 mg l^{-1} by pure-oxygen generator (AS-12, AirSep, NY, USA). The MCR was fed in a fill and draw mode with a mixture of raw leachate as a sole carbon source and Nutrient/Mineral/Buffer solution (NMB) (Table 2) at a loading rate of 400 mg l^{-1} d^{-1} COD in order to maintain stable pH and nutrient requirements for 10 months at ambient temperatures. Feeding was done per 2 d and biomass concentration as MLVSS was held 3200 ± 100 mg l^{-1}. The settleability of biomass in pure-oxygen MCR was excellent and the high concentration of ammonia-nitrogen was rapidly converted into nitrate via nitrification.

2.3 Batch experimental procedures

2.0 l glass bottle reactor with a working volume of 1.8 l was used in batch experiments. The configuration of this batch reactor was absolutely similar with the pure-oxygen MCR except for smaller volume than pure-oxygen MCR. The inoculated seed culture from pure-oxygen MCR was washed with distilled water several times to minimize the interference of hardly biodegradable compounds accumulated in pure-oxygen MCR through long operation. The pH was usually maintained at 7.0 ± 0.4 and magnetic stirrer was introduced to prevent settling of sludge. Oxygen was supplied via pure-oxygen generator at a constant flow rate to held DO concentration of 8 ± 1.0 mg l^{-1}. The assessment of the biokinetic constants associated with the readily biodegradable portion of the feed leachate, S_{PM}, and S_I of feed leachate was carried out through two steps of

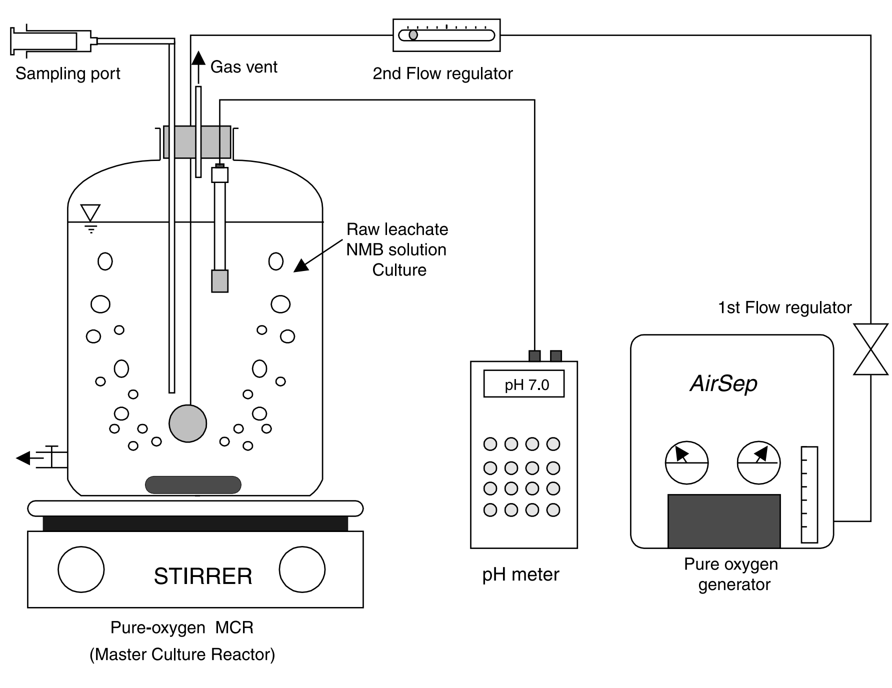

Fig. 2. Schematic diagram of pure-oxygen Master Culture Reactor

Table 2. Nutrient/Mineral/Buffer composition

Compounds	Concentration (mg/l)
$CoCl_2\ 6H_2O$	0.01
$FeSO_4\ 7H_2O$	0.12
$ZnSO_4\ 7H_2O$	0.03
$MnSO_4\ H_2O$	0.036
$CaCl_2\ 2H_2O$	0.10
$MgSO_4\ 7H_2O$	0.10
KH_2PO_4	270
NH_4Cl	100
K_2HPO_4	350
NaH_2PO_4	50

batch experiments. The trend of excess biomass produced with respect to various initial soluble substrate to biomass ratios ($S_{T0.inf}/X_0$) was investigated. Determined values of biokinetic constants, Y_S, K_S, k_d, μ, and k, and S_R incorporatin both S_{PM} and S_I were used for predicting the residual COD of the reactor treating leachate under pure-oxygen conditions. The detailed experimental plans are summarized in Table 3.

2.4 Determination of biokinetic constants and modeling

The most common equation in order to describe substrate consumption rates in a biological wastewater treatment is the Monod model, a relationship between the residual concentration of the growth-limiting substrate (S_S) and the specific growth rate of biomass (μ) [12, 19]. However, more sophisticated and accurate models for biodegradation of wastewaters, especially for leachate, should simultaneously consider both biodegradable COD and inert COD from original feed wastewaters and microbial activities. For the determination of the biokinetic constants associated with the readily biodegradable COD in leachate, the method developed by Roinson and Tiedjie (1983), and Dang et al. (1989) was used. This method involves non-linear curve fitting techniques for parameter estimation, in batch reactors started with known values of S_{S0} and X_0, in accordance with the following fundamental relationships [20, 21]:

$$-\frac{dS_S}{dt} = \frac{\mu_{max}}{Y_S}\frac{S_S X}{K_S + S_S} = \frac{kS_S X}{K_S + S_S} \quad , \qquad (13)$$

$$\frac{dX}{dt} = Y_S\left(-\frac{dS_S}{dt}\right) - k_d X = \left(\frac{Y_S k S_S}{K_S + S_S} - k_d\right)X \quad , \qquad (14)$$

$$S_{t(n+1)} = S_{t(n)} - dS_{t(n+1)} + S_{R(t)} \quad , \qquad (15)$$

$$S_{R(t)} = S_I \times \frac{t}{a2t_{1/2}} \quad . \qquad (16)$$

Biokinetic and stoichiometric constants based on the relationship between readily biodegradable substrate consumption and biomass production during substrate enriched period do not appropriately account for the effect of S_{PM} and S_I during substrate depletion period, and microbial population dynamics at the later part of batch experiments. Therefore, a new parameter, the relative residual COD with time ($S_{R(t)}$), was introduced in this work to predict accurately overall residual COD of effluent at various time. $S_{R(t)}$, time dependent parameter, consists of four parameters such as S_I, a, t, and $t_{1/2}$ (Eqs. (15)–(16)). Its extent of contribution on total residual COD is greater in substrate depletion period. Therefore, degree of contribution of $S_{R(t)}$ remains low before the beginning of biodegradable substrate deficiency occurs, but its effect gradually increases with time as available substrate becomes limited.

3 Results and discussion

3.1 S_I and S_{PM} of raw leachate

Sometimes, pollutant concentration of biologically treated leachate exceeds discharge standards due to inappropriate estimation or consideration of S_I and S_{PM}. Careful consideration of S_I and S_{PM} is very important in the process design of biological leachate treatment to optimize process structure and operating parameters and to estimate effluent residual COD. Four aerobic batch reactors were operated and COD was periodically measured until a plateau value was reached for 120 h. Two of these were fed with

Table 3. Summary of experimental plans

Step	Purpose	Materials added	$S_{T0.inf}/X_0$	Function
1	Define biodegradability, inert COD, and biomass production with respect to diverse $S_{T0.inf}/X_0$ ratios	Seed + NMB + 3 levels of raw leachates (250, 500, 1000 mg l^{-1} as COD) Seed + NMB + glucose (270, 500 mg l^{-1} as COD) Seed + NMB + pre-ozonated leachate (500 mg l^{-1} as COD) Seed + NMB + 3 levels of anaerobically treated leachates (250, 360, 500 mg l^{-1} as COD)	<2.0	Tests units
		Seed + NMB		Blank
		NMB + raw leachate		Abiotic control
2	Biokinetic tests and Modeling	Seed + NMB + 5 levels of raw leachates (109, 568, 620, 720, 864 mg l^{-1} as COD) Seed + NMB + 4 levels of raw leachates (250, 500, 800, 1000 mg l^{-1} as COD)	<2.0	Test units

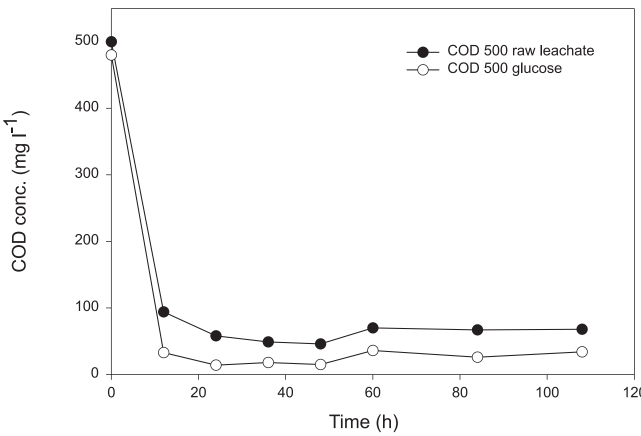

Fig. 3. Determination of S_{PM} and S_I

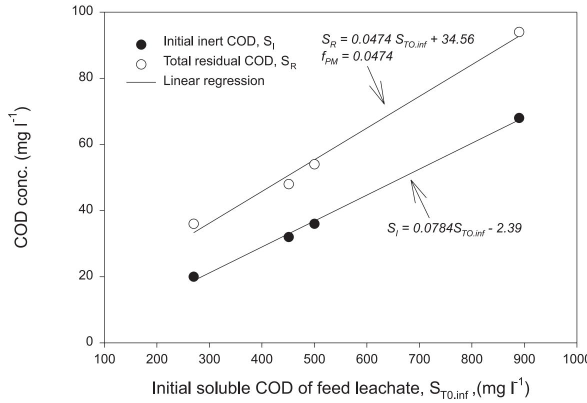

Fig. 4. Relationship between S_R and S_I and $S_{T0.inf}$

the raw leachate as a sole carbon source in 250 mg l^{-1} and 500 mg l^{-1} COD, respectively. Other two reactors received glucose with the same initial CODs in parallel. From the results shown in Fig. 3, if inert COD produced by microbial activities with respect to different substrates in the same concentration of COD were identical, the residual plateau value (S_{PM}) for glucose 500 mg l^{-1} COD was 22 mg l^{-1}. Consequently, the difference between the plateau values of glucose and raw leachate reactor (S_I) was 36 mg l^{-1}.

However, further consideration on S_{PM} is required, because for the same initial concentration of glucose and leachate as COD utilized in bacterial reaction the production of S_{PM} can be different. For instance, when the leachate containing high concentration of inhibitors was introduced in a microbial batch assay, the required maintenance energy and the possibility of cell destruction may increase compared with glucose having the same COD concentration. The coefficient, f_{PM}, associated with the inert COD produced via microbial activities was 0.0474 as measured at the plateau values. From the results of Fig. 4 illustrating a linear plot of the measured values of residual COD with respect to diverse initial COD, the total residual COD of the effluent (S_R) was explained as Eq. (17) by applying Eq. (12), and the fraction value of initial inert COD in feed leachate (f_I) was approximately 7.8%:

$$S_R = 0.0474\, S_{T0.inf} + 34.56 \ , \qquad (17)$$

$$S_I = 0.0784\, S_{T0.inf} - 2.39 \ . \qquad (18)$$

However, as can be seen in Fig. 5, values of S_R at the later part of experiments (at t = 84 h) were higher than those of plateau period (at t = 24–48 h) due to the cell lysis and external decay being measured as loss of biomass weight, number or activity. Consequently, it is expected that the value of S_R is quite dependent on the biological solids retention time in actual activated sludge processes.

Figure 6 describes the trend of substrate depletion and inert COD formation via microbial activities with respect to various kinds of feeds such as raw leachate, anaerobically pre-treated leachate and glucose. According to the results, at the beginning of experiments, when biodegradable organic portion is high in leachate, the COD concentration decreased relatively fast then reached a plateau value for internal decay period. After internal decay period, residual COD gradually increased due to the excretion of inert COD by cell lysis then decreased again in small quantity by the re-growth of bacteria. The increased amount of inert COD produced via microbial activities was the highest for anaerobically pre-treated leachate (S_{PM} = 124 mg l^{-1}, at t = 85 h). This result does not meet the assumption in Eq. (8) and shows a possible dependency of S_{PM} on wastewater types. The trend of substrate depletion of this work is in good agreement with bacterial

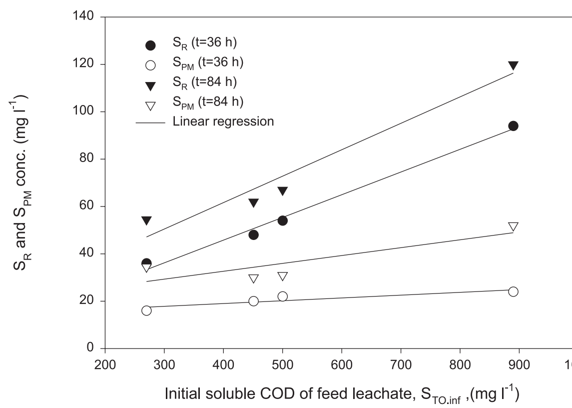

Fig. 5. Changes of S_R and S_{PM} with respect to different $S_{T0.inf}$ at different time

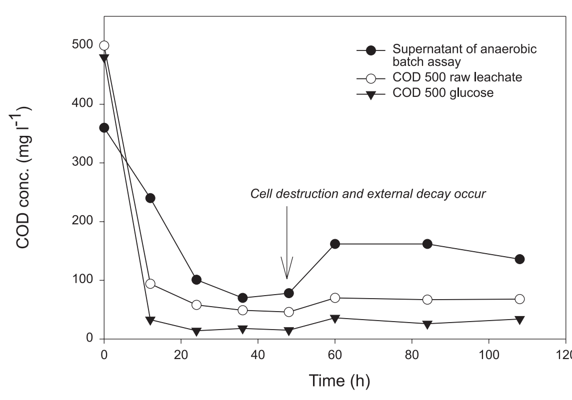

Fig. 6. Substrate depletion and bacteria mediated inert COD formation with respect to various kinds of substrates

re-growth (or cryptic growth) model caused by the subsequent assimilation of destroyed cell materials as a secondary substrate at the end of a batch assay. The internal decay does not seem to reduce the number of bacteria significantly, but decreases the weight and activity of bacteria by the consumption of intracellular storage compounds. Whereas, significant reduction of bacterial number, activity and weight can be caused by external decay. Kaprelants and Kell (1996), however, suggested that most bacteria probably become dormant for a long time, instead of dying during the period of substrate depletion. Consequently cell death due to the deficiency of substrate probably hardly ever occurs [23].

3.2 Effect of $S_{T0.inf}/X_0$ ratios on excess sludge production

To evaluate the effect of maintenance energy requirements on the excess sludge production, a set of batch assays were carried out with respect to various ratios of $S_{T0.inf}/X_0$. As shown in Fig. 7, decreasing the supply of substrate per unit biomass from 0.41 to 0.032 g g^{-1} h^{-1} resulted in about 30% reduction in the observed yield. This result may be caused by the prior allocation of substrates into maintenance function to new cell synthesis and internal cell decay or lysis. These results were similar with the experimental data by Low et al. (1999). Figure 8 shows the effect of substrate supply per unit initial biomass on the rate of excess biomass production per hour. In this figure, decreasing the supply of substrate per unit biomass from 1.0 to 0.094 g g^{-1} resulted in gradual decrease of about 28% in the biomass production per hour. However, after the supply of substrate per unit biomass of 0.094 g g^{-1}, the excess biomass production rate dramatically decreased. Therefore, reduction of excess biomass production could be expected by increasing biomass concentration. On the other hand, relatively low $S_{T0.inf}/X_0$ ratio can be held for high concentration of influent due to high capability to maintain biomass in the aeration tank supplemented with pure-oxygen. The biomass concentration is controlled easily by bacterial solids retention time, moreover, increasing sludge ages makes it possible to maintain slow growing nitrifiers such as *Nitrosomonas* and *Nitrobactor* without washing out in the reactor. Therefore high concentration of ammonia nitrogen can be easily removed via nitrification in pure-oxygen processes. Further more, Knudson et al. (1982) proposed that pure-oxygen process can achieve improved sludge settleability and lower net sludge production per unit BOD removed compared to conventional air-activated sludge process. Consequently, the pure-oxygen process may have high potential to be applied into on-site leachate treatment plants.

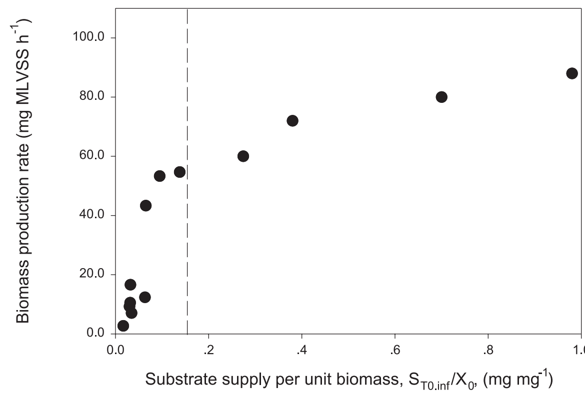

Fig. 8. Effect of substrate supply per unit initial biomass on the excess biomass production

3.3 Optimum ratios of $S_{T0.inf}/X_0$ to reduce both inert COD and excess biomass formation

The low $S_{T0.inf}/X_0$ ratios mean the low excess biomass production. But, it also can produce the high concentration of bacteria mediated inert COD due to the cell destruction caused by available substrate deficiency. Therefore, determination of optimum $S_{T0.inf}/X_0$ ratios to decrease the productions of both sludge yields and bacteria mediated inert COD is necessary prior to process design. According to the results of Fig. 9, the optimum $S_{T0.inf}/X_0$ ratios were in the range of 0.2–0.6 under pure-oxygen conditions.

3.4 Determination of biokinetic coefficients and modeling

Chudoba et al. (1992) have pointed out the effect of initial substrate to biomass concentration ($S_{T0.inf}/X_0$) ratios on the batch assays for the determination of biokinetic coef-

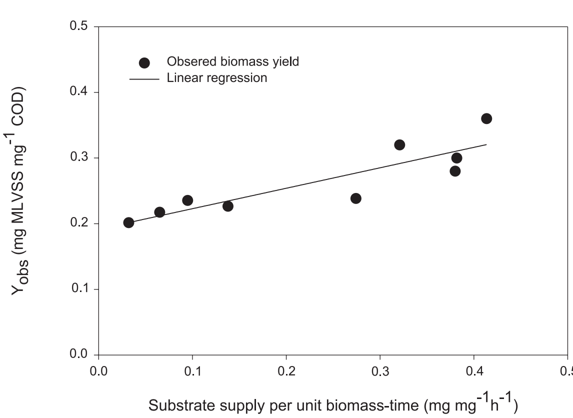

Fig. 7. Effect of substrate supply per unit biomass on the observed biomass yields

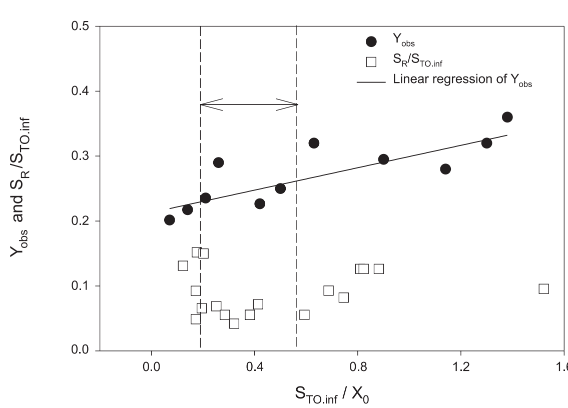

Fig. 9. Optimum $S_{T0.inf}/X_0$ ratios to reduce simultaneously both Y_{obs} and S_R

ficients. They suggested that the ratios should be less than 2.0, in order to minimize the changes of bacterial growth conditions in both physiological state and community structure away from those of the original plant treatment processes. Hence, batch reactors were operated with the low $S_{T0.inf}/X_0$ ratio in this research (<2.0). To evaluate the biokinetic constants, Y_S, k_d, and μ, related with readily biodegradable portion of raw leachate, the experiments were run for 48 h, then the obtained constants were used to evaluate the K_S and k by using non-linear regression technique. The kinetic and stoichiometric constants evaluated from the results of these experiments are summarized in Table 4 together with literature data from previous researchers. The obtained average biomass yield value was 0.36. This small yield value compared with air-activated systems implies the reduction of plant operating costs for excess sludge disposal.

The simple assumption in the traditional mathematical models for biological wastewater treatments was that its concentration of organics can be described by a single parameter such as BOD, TOC, or COD. In contrast, in the model formulated in this study, readily biodegradable COD and initial inert COD from feed substrate were introduced as well as bacteria mediated inert COD, separately. The results of mathematical modeling for substrate depletions are illustrated in Fig. 10, which clearly shows that the effluent soluble COD could not be lowered below 92 mg l^{-1} due to contribution of both S_{PM} and S_I. The predicted values 1 represent the simulation results by using Eqs. (13) and (14) without the consideration of S_I and S_{PM}. The simulation results fitted well in the beginning period but at the later part were not in good agreement with the measured data due to the missing of considering S_I and S_{PM}. The predicted values 2, in contrast, was expanded to include $S_{R(t)}$ which represents the relative total residual COD with time (Eqs. (15) and (16)) and appeared to be in good agreement with the observed data for whole experiment. The value of stoichiometric constant, a, experimentally measured, was 1.62.

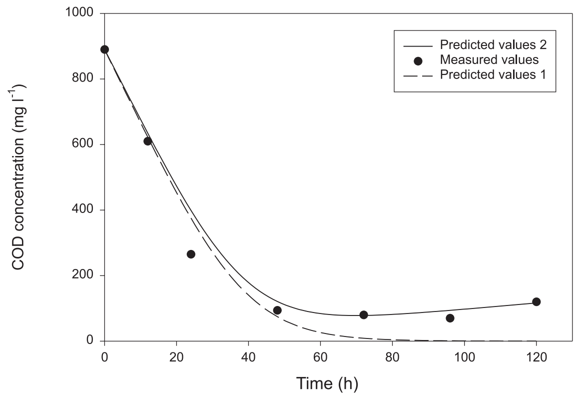

Fig. 10. Mathematical modeling for the prediction of residual COD

4
Conclusion

The effluent residual soluble COD was entirely composed of S_I and S_{PM} and the amount of S_{PM} formed after the consumption of readily biodegradable substrate was diverse with wastewater types. In principle, satisfying maintenance energy requirements is prior to providing the energy for new cell synthesis. Therefore, increasing the amount of substrate uptake for maintenance (low $S_{T0.inf}/X_0$ ratio) may decrease the net sludge production. Pure-oxygen process can maintain relatively low $S_{T0.inf}/X_0$ ratio for high conentration of influent because of the ability to maintain higher biomass concentrations in the aeration tank. Furthermore, the pure-oxygen process has rapid organics and ammonia nitrogen removal efficiency, since increased solids retention time can hold high concentrations of heterotrophs as well as slow growing nitrifiers without washing out in the reactor. Consequently, the pure-oxygen process may have high potential to be applied into on-site leachate treatment plants having space restriction. The low $S_{T0.inf}/X_0$ ratios mean the low sludge yields. But, too much lower $S_{T0.inf}/X_0$ ratios also may result in gradual increase in the bacteria mediated inert COD. Therefore, determination of optimum $S_{T0.inf}/X_0$ ratios to decrease the productions of both sludge yields and bacteria mediated inert COD is necessary prior to process design. According to the results of this work, the optimum $S_{T0.inf}/X_0$ ratios were in the range of 0.2–0.6 under pure-oxygen conditions.

Table 4. Biokinetic and stoichiometric constants for the biological leachate treatment (modified from [16])

Substrate type	Y	k_d (d^{-1})	k	K_s (mg l^{-1})	μ_{max} (d^{-1})	Basis	BOD/COD	O_2 supply	Remarks
Leachate	0.33	0.0025	0.75	21.4		BOD	>0.4	air	Cook and Foree (1974)
Leachate	0.40	0.05	0.60	175		COD	>0.4	air	Uloth and Mavinic (1977)
Leachate	0.59	0.115	1.80	182		COD	>0.4	air	Palit and Qasim (1977)
Leachate	0.42	0.025				COD		air	Chain and DeWalle (1977)
Leachate	0.19		10.78	921	1.98	BOD	0.618	air	Kimpo landfill (1995)
Leachate	0.34		5.35	470	1.86	BOD	0.615	air	Kimpo landfill (1995)
Leachate	0.36	0.022	1.557	612	0.56	COD	0.65–0.75	O_2	This research
Synthetic wastewater	2.15	0.16	1.384	54.11		TOC		O_2	Choi (1997)
Domestic wastewater	0.4 –0.8	0.025–0.075	2–10	25–100		BOD		air	Ministry of Environment

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