Desalination and Water Treatment
www.deswater.com
51 (2013) 2109–2115
February

doi: 10.1080/19443994.2013.734586

A flexible aeration strategy based on the removal of COD and MLSS in treating tomato paste wastewater

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Received 2 September 2011; Accepted 25 July 2012

ABSTRACT

The influent chemical oxygen demand (COD) of tomato paste wastewater changes with the quality of the raw material without any evident trend. The required aeration also changes irregularly during treatment. If the actual aeration rate is set at maximum and does not change, the treating cost increases. Thus, an adaptable aeration strategy based on simple data, such as the removal of COD and mixed liquor suspended solids (MLSS), must be established. The plug-flow activated sludge system of Shihezi Tianye Tomato Products Co., Ltd., was used to establish the relationship between the theoretical aeration rates and the removal of COD and MLSS in different regions. The calculation bases of the theoretical aeration rates at different COD loadings were determined. A flexible aeration strategy based on the removal of COD and MLSS was used to analogically calculate and compare the actual aeration patterns from 2010. The proposed method can decrease aeration rate by 8%.

Keywords: Tomato paste wastewater; Plug-flow activated sludge system; Aeration rate; Kinetics

1. Introduction

Millions of tons of untreated tomato paste wastewater are discharged every year in Xinjiang, China, leading to serious pollution and water resource shortage, thus limiting the development of tomato paste processing industries [1,2]. The sludge must be acclimated every year due to the seasonal nature of its production. The treatment ability could not be guaranteed, which influences the treatment effect. In our previous research, a mixture of flora with seven strains was built to solve this problem. For the past three years, the treated effluent quality of Shihezi Tianye Tomato Products Co., Ltd., has met the Chinese National Second-Grade Effluent Standard of GB 8978-1996 [3]. The cost per m^3 was $0.087, and the electricity charge accounted for 63%.

Electricity is used for the power aeration systems in a wastewater treatment plant (WWTP). Aeration provides oxygen to maintain microbial growth and organic pollution degradation [4]. Dissolved oxygen (DO) concentration should be higher than 2 mg/L to assure micro-organism growth. Aeration is set at a much higher rate than the theoretical concentration required to prevent sludge, and the treatment effects were damaged due to low DO concentrations. However, this practice increases operation costs [5,6]. A plug-flow activated sludge system has a gradient of oxygen requirements along the reactor. However, in an actual treatment system, the aeration power is

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homogeneous. The characteristics of tomato paste wastewater change greatly along the production season. For instance, chemical oxygen demand (COD) can range from 400 to 2,000 mg/L, which indicates different aeration power requirements. However, aeration in actual production often remains unchanged, which increases costs; in turn, higher costs result in more illegal discharge.

A standard practical strategy for reducing energy costs is to adjust the aeration rate to the actual demand of oxygen [7]. The commonly used theoretical calculation of aeration in the design is activated sludge model No. 1 (ASM 1). The carbon oxidation process, nitrification, and denitrification are included in ASM 1, which considers 13 components of wastewater [8]. ASM 1 is very complex; thus, it is difficult to use as a control model. The accuracy of calculation depends on the parameter values of the model. The parameter values of different wastewaters differ greatly, especially in the case of tomato paste wastewater. In China, the aeration calculation of the activated sludge process in an actual engineering design often complies with the Code for Design of Outdoor Wastewater Engineering (GB50014-2006) [9], which includes the aerobic reaction, anoxic reaction, denitrification reaction, and some processes that affect oxygen demand, such as the removal of biochemical oxygen demand (BOD_5) and sludge growth. However, in practice, the aeration calculated from this method is quite different from the actual demand. Many tomato paste WWTPs exist, but the specific calculation process of aeration is not found in the related literature. Thus, the purpose of the current work is to establish an adaptable strategy based on simple data measurements that can be applied conveniently and can reduce costs at the same time.

Most WWTPs can detect mixed liquor suspended solids (MLSS) and COD. Controlling the aeration through these indicators would not increase the burden in the plant. MLSS and the removal of BOD_5 or COD are the important bases for most aeration calculations. Thus, in this study, the relationships between MLSS and the removal of COD, and the aeration rate of different parts in the plug-flow activated sludge system were assessed using actual data from 2010. The theoretical aeration rates of different regions in a WWTP were calculated based on the removal of COD and MLSS under different influent COD. The calculating bases under different conditions were also determined. Finally, aeration using an adaptable strategy based on COD removal and MLSS concentration was calculated using actual data from 2010, and then compared with the actual aeration.

2. Materials and methods

2.1. Reactor and operation

The WWTP of Shihezi Tianye Tomato Products Co., Ltd., consists of an equalization tank, seven aeration tanks, and a secondary sedimentation tank (Fig. 1). Each tank measures $19\,m \times 10\,m \times 5\,m$ ($L \times W \times H$), with a total volume of $950\,m^3$. Fiber packing was added to aeration tanks No. 3, 4, and 5 to increase sludge concentration. A total of seven aeration tanks were divided into three regions according to the filler: the A region includes aeration tanks 1 and 2; the B region includes aeration tanks 3, 4 and 5; and the C region includes aeration tanks 6 and 7. The aeration rate was $810\,m^3/min$, which was provided by two root blowers (24 kW/h). Average influent flow was $352\,m^3/h$, ranging from 300 to $360\,m^3/h$. The hydraulic retention time (HRT) in every reactor tank and the total HRT were 2.69 and 18.83 h, respectively.

2.2. Seed sludge

The mixed flora included seven aerobic strains [10] that were screened from acclimated sludge which originated from the tomato paste wastewater drainage system in Shihezi, China. The seven strains were divided into two types: degradation dominant bacteria, including *Bacillus subtilis* (JH642), *Pseudomonas putida* (KT2440), *Bacillus megaterium* (DSM319), and *Citrobacter koseri* (BAA-895) and floc-forming dominant bacteria, including *Bacillus cereus* (F65185), *Bacillus* sp. (B-14911), and *Pantoea agglomerans* (WAB1913). The strains were cultured separately in a shake flask and subsequently mixed in a 140 L container.

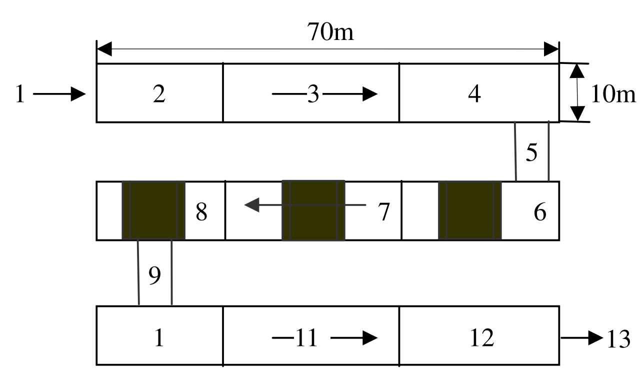

Fig. 1. Schematic diagram of the system: (1) influent water (2) equalization tank (3, 4); aeration tank (A region); (5) aqueduct I (6, 7, 8); fiber tank (B region); (9) aqueduct II; (10, 11, 12) aeration tank (C region); (12) secondary settling tank; and (13) effluent water.

2.3. Theoretical calculation

Tomato paste wastewater has low total nitrogen (TN) ($\leq$2 mg/L) [11]; thus, the oxygen requirement for ammonia oxidation could be not considered. Given that DO could not reach saturation in the existing conditions, the oxygen requirement can be calculated by subtracting the amount of COD converted to biomass from the total removed COD [12].

The total oxygen consumption rate, O_2, can be expressed by a mass balance, where the first term on the right side describes the equivalent COD requirements and the second term describes the amount of COD converted to biomass; this is given by:

$$\frac{dO_2}{dt} = \frac{Q}{V}(S_i - S_e) - \beta\frac{dx}{dt} \quad (1)$$

where β is the conversion factor of biomass to COD (i.e. 1.2 mg COD/mg MLSS). The theoretical aeration requirement (Q_{air}) was calculated from the oxygen consumption rate, O_2, considering a constant (4.0), the specific oxygen transfer efficiency (η), and reactor depth (m) [13]:

$$Q_{air} = \frac{O_2}{4.0m\eta} \quad (2)$$

2.4. Analytical methods

The seasonal wastewater treatment lasted for 46 days (from 13 August 2010 to 29 September 2010). Samples were collected daily from the inlet, aqueduct I, aeration tank 4, aqueduct II, aeration tank 7, and outlet. The COD and MLSS were measured using standard methods [14]. DO was measured using a DO electrode (51970-03 DO) connected to a DO meter (sension156, HACH COMPANY, USA). All measurements were repeated three times. The relationships between Q_{air} and the removal of COD and MLSS were fitted using Matrix Laboratory (MATLAB).

3. Results

3.1. COD removal efficiency

Throughout the treatment process, effluent COD ranged from 82 to 150 mg/L (142 mg/L average effluent COD), which was lower than the discharge standard ($\leq$150 mg/L). On the other hand, the TN and total phosphorus (TP) in the tomato paste wastewater were slightly low, meeting the discharge standard of TN $\leq$ 25 mg/L and TP $\leq$ 1 mg/L, respectively (GB 8978-1996). Combining effluent COD, TN, and TP, the effluent quality met Chinese National Second-Grade Effluent Standard of GB 8978-1996 [15].

3.2. Theoretical aeration requirements

Figs. 2–4 show the relationships between the removal of COD and Q_{air} (theoretical aeration rate) in different regions. The fitting types are shown in the following expressions:

$$\text{(A region)}\ y = \frac{12.83x1}{(151 + x1)} \quad (3)$$

$$\text{(B region)}\ y = \frac{16.19x1}{(644 + x1)} \quad (4)$$

$$\text{(C region)}\ y = \frac{11.2x1}{(247.4 + x1)} \quad (5)$$

Figs. 5–7 show the relationships between the MLSS and Q_{air} (theoretical aeration rate) of different regions. The fitting types are shown in the following expressions:

$$\text{(A region)}\ y = \frac{12.76x}{(538.7 + x)} \quad (6)$$

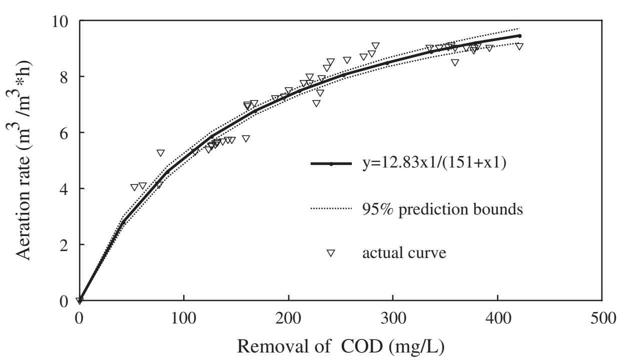

Fig. 2. Relationship between the removal of COD and Q_{air} in A region.

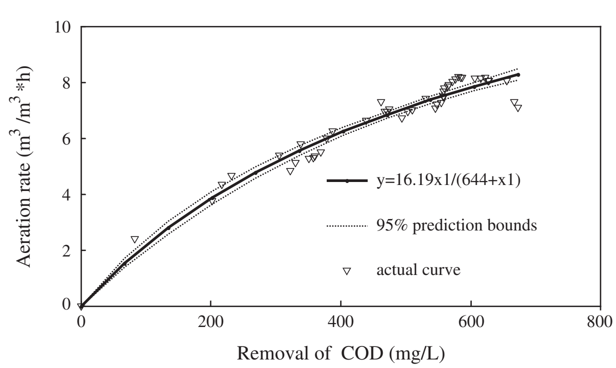

Fig. 3. Relationship between the removal of COD and Q_{air} in B region.

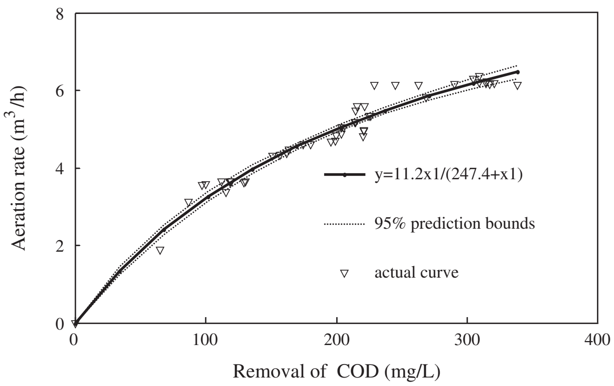

Fig. 4. Relationship between the removal of COD and Q_{air} in C region.

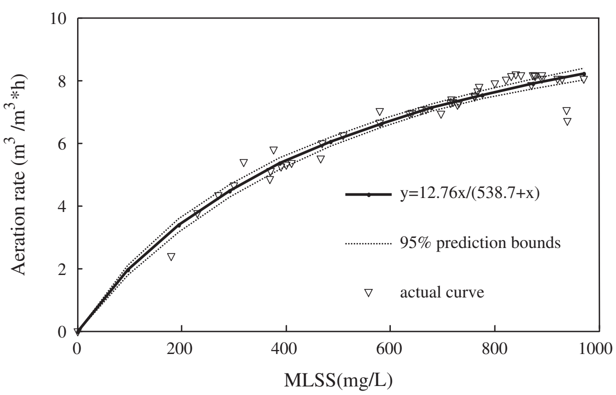

Fig. 5. Relationship between MLSS and Q_{air} in A region.

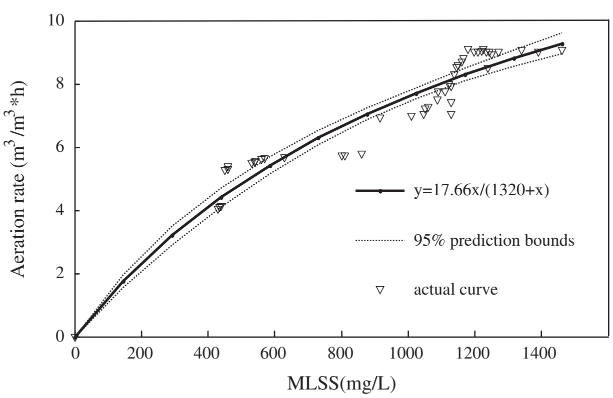

Fig. 6. Relationship between MLSS and Q_{air} in B region.

$$\text{(B region) } y = \frac{17.66x}{(1,320 + x)} \tag{7}$$

$$\text{(C region) } y = \frac{10.08x}{(584.6 + x)} \tag{8}$$

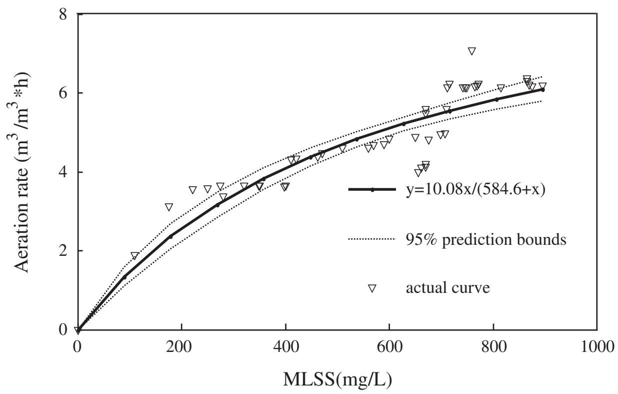

Fig. 7. Relationship between MLSS and Q_{air} in C region.

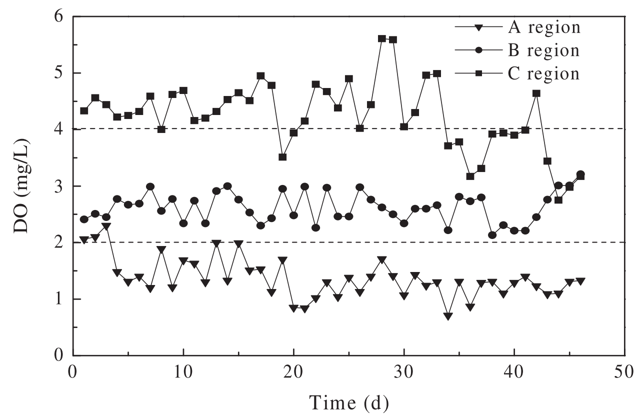

Fig. 8. DO concentrations in different WWTP regions.

3.3. Practical aeration rates and DO concentrations

The aeration rates in all aeration tanks were the same in 2010. The aeration tanks had 6,650 m^3 whole volume, resulting in $7.3\,m^3/(m^3\,h)$ aeration rate for all tanks. Fig. 8 shows the DO concentrations of different regions. DO concentration in the A region was less than 2.0 mg/L, which was lower than the actual lower limit of DO concentration in the activated sludge system. This was attributed to two reasons: 1) the DO concentration of the influent was less than 0.4 mg/L and 2) COD loading was higher, thus consuming more oxygen. The aeration rate at the A region should be increased to ensure proper aeration distribution along the tanks and to overcome mass transfer limitations. On one hand, DO concentration in the B region ranged from 2.0 to 3.0 mg/L, which was the same as the activated sludge system [16]. However, this value was lower than that of the biological contact oxidation process (4.0 mg/L). On the other hand, DO concentration in the C region was higher than 3.4 mg/L, which represented a waste of energy costs.

4. Discussion

4.1. Theoretical aeration rates in different conditions

The main pollutants of tomato paste wastewater are sugar and organic acids. Particularly for tomato paste WWTPs, Chinese environmental regulators have become stricter with the level of COD allowed to be discharged in freshwater [17,18]. The characteristics of tomato paste wastewater change significantly throughout the production season. For example, the influent COD ranged from 400 to 1,600 mg/L in 2010. Therefore, COD loading can be classified into three ranges: low (400–800 mg/L), moderate (800–1,200 mg/L), and high (1,200–2,000 mg/L) loading. The periods of low, moderate, and high loadings were 11, 20 and 15 days, respectively. The data inserted in the formulas were the average values in the period.

The average theoretical aeration rates of low loading in the three regions were 5.4, 4.9, and 3.6 $m^3/(m^3 h)$, respectively, which were calculated from the fitting of the COD removal and Q_{air}. These values were lower than the practical aeration rate. The lower theoretical aeration rates were proportional to the lower COD load. However, the aeration rates in three regions were gradually reduced, following the same pattern in the plug-flow activated sludge system. The values calculated from the fitting types of MLSS and Q_{air} were slightly lower than those calculated from the removal of COD and Q_{air}, which were 5.3, 4.5, and 3.1 $m^3/(m^3 h)$, respectively. Lower loadings usually exist in the early treatment process. To rapidly increase the sludge concentration, the aeration rate should be slightly higher. Thus, the required aeration rates for the three regions were calculated from the COD removal when the influent COD ranged from 400 to 800 mg/L.

The average theoretical aeration rates for moderate loading in the three regions of the WWTP were 7.2, 7.1, and 5.1 $m^3/(m^3 h)$, respectively. These values were calculated from the fitting types of the removal of COD and Q_{air}. With the increase in the influent COD, the required aeration rates also increased. The theoretical aeration rates of the A and B regions were close to the practical aeration rate, but that of the C region was lower. The trends in the three regions were the same as those in low loading. However, the trends in the three regions changed when MLSS and Q_{air} were calculated, resulting in the changed values of 7.9, 8.0, and 4.5 $m^3/(m^3 h)$, respectively. The theoretical aeration rates of the A and B regions were evidently higher than those calculated from the removal of COD and Q_{air}. The sludge concentration could not be decreased in normal conditions. Thus, the value of MLSS was slightly higher than average, which led to a higher result. However, the result of the B region was higher than that of the A region, and was different from the trend calculated from the removal of COD and Q_{air}. The loss of sludge increased gradually with the increase in hydraulic loading; hence, the fluctuation of MLSS in the A region was evidently larger than that in the B region, leading to a lower average value and calculation result.

To maintain the sludge activity, aeration should not decrease (i.e. DO concentration must be higher than 2 mg/L). Thus, the required aeration rates for the three regions were calculated from the MLSS when the influent COD ranged from 800 to 1,200 mg/L.

The average theoretical aeration rates of high loading in the three regions were 9.1, 7.8, and 5.8 $m^3/(m^3 h)$, respectively. These were calculated from the fitting type of COD removal and Q_{air}. With the increase in the influent COD, the theoretical aeration rates began to exceed the practical aeration rates. This can be attributed to the poor treatment effect (effluent COD $\geq$ 150 mg/L). However, the theoretical aeration rate of the C region was also evidently lower than the practical aeration rate. This result indicated that overall aeration could be achieved by adjusting the aeration ratio of different regions, thus avoiding the need to add new root blowers. The values calculated from the fitting types of MLSS and Q_{air} were 8.2, 8.5, and 4.8 $m^3/(m^3 h)$. The value of the A region was lower than that calculated from the removal of COD and Q_{air}; this showed a different trend from that of moderate loading. The higher influent COD was mainly caused by the large amounts of broken tomato flesh in the influent. Most of these tomato flesh remnants precipitated in the A region, thereby causing more problems. The sludge growth needed a certain time and was limited by DO; furthermore, the increase in MLSS was comparatively slow. Therefore, the theoretical aeration rates calculated from the fitting types of the removal of COD and Q_{air} were evidently higher than those calculated from the model fitting of MLSS and Q_{air}, indicating that the treating effect increased with increased aeration. The trends of the band C regions were consistent with those of moderate loading. Therefore, the required aeration rates of the B and C regions were also calculated from the MLSS when the influent COD ranged between 1,200 and 2,000 mg/L.

4.2. Aeration using an adaptable strategy

In the actual treating process, the aeration rate cannot be changed. Therefore, three ranges of aerations were calculated under the setting data that were selected according to the practical data in 2010. In low loading, the aerations were calculated from the

Table 1
Aeration rates in different conditions

	Aeration rate (m^3/m^3 h)		
	A region	B region	C region
Low loading	6.1	5.2	3.8
Moderate loading	7.8	8.0	4.6
High loading	8.7	8.4	4.9

removal of COD at a setting of 570 mg/L (influent COD 700 mg/L and effluent COD 130 mg/L). In moderate loading, the aerations were calculated from the MLSS at settings of 850, 1,100, and 500 mg/L in all three regions. In high loading, the aeration of the A region was calculated from the removal of COD at a setting of 1,350 mg/L (influent COD 1,500 mg/L and effluent COD 150 mg/L). The aerations in the B and C regions were calculated from the MLSS, with settings at 1,200 and 550 mg/L. The aeration rates of all three regions in different conditions are shown in Table 1.

The theoretical aeration rates in the three ranges were 561, 776, and 831 m^3/min, respectively. The maximum value was a little higher than the actual aeration. Thus, there would be no necessity to increase the number of root blowers. If using the same aeration, the "prevailing aeration" rate increased to 969 m^3/min, reaching 119.68% of the actual aeration in high loading and necessitating the increased number of root blowers.

Throughout the entire treatment process (46 days), the aeration volume could be decreased by 8% if the flexible aeration strategy is used; the treatment cost could also be decreased by 5% (1,708 $).

In actual production, aeration can be calculated by the measured influent COD and MLSS every day. However, frequently adjusting the aeration is troublesome and difficult. Thus, a better method is suggested as follows. In a period of time, the influent COD and MLSS used for calculation are set slightly higher than the average values used for many years. When the influent COD changes, the settings of the influent COD and MLSS would change and the aeration must be recalculated.

5. Conclusions

The regression model was used to calculate the COD removal and Q_{air} and MLSS and Q_{air} in different regions in the plug-flow activated sludge of the tomato paste WWTP with the following results: $y = \frac{12.83x1}{(151+x1)}$, $y = \frac{16.19x1}{(644+x1)}$, $y = \frac{11.2x1}{(247.4+x1)}$, $y = \frac{12.76x}{(538.7+x)}$, $y = \frac{17.66x}{(1{,}320+x)}$, and $y = \frac{10.08x}{(584.6+x)}$, respectively. The bases of the theoretical aeration rates at different conditions were assessed from the COD removal in low loading rates. In high loading rates, the theoretical aeration rates of the A region were calculated from the removal of COD; those of the B and C regions were calculated from the MLSS concentration. The highest aeration rate of the whole WWTP adaptable strategy was 831 m^3/min. This was comparable to the actual aeration (810 m^3/min) indicating that the number of roots blowers need not be increased. The volume of aeration could be decreased by 8% if a flexible aeration strategy is used. Furthermore, treatment costs could be decreased by 5% (1,708 $).

Nomenclature

m	—	reactor depth, m
O_2	—	oxygen consumption, kg O_2 day^{-1}
Q_{air}	—	air flow rate, $m^3/(m^3h)$
S_e	—	COD in effluent, mg/L
S_i	—	COD in influent, mg/L
t	—	time, h
V	—	aeration tank volume, m^3
β	—	mg COD/mg MLSS
η	—	specific oxygen transfer efficiency, m^{-1}
y	—	aeration rate, $m^3/(m^3h)$
x	—	MLSS, mg/L
$x1$	—	removal of COD, mg/L

Acknowledgments

This study was partially supported by the National Natural Science of China (Grant No. 51068024). Assistance from the Laboratory for Green Processing of Chemical Engineering, Xinjiang Bingtuan and Shihezi Tianye Tomato Products Co., Ltd., are also acknowledged.

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