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Biological heat potential and temperature effect of an autothermal thermophilic aerobic treatment (ATAT) system

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Abstract: *This study focused on the evaluation of the specific biological heat potential (h_b) of a food-processing artificial wastewater in the autothermal thermophilic aerobic treatment (ATAT) system. A novel experimental method was developed to evaluate the h_b value by using the heat balance model under the steady state. This system was daily fed with oily and artificial wastewater at 21460 mg l^{-1} COD. The sludge retention time (SRT) was controlled at 15 days. The results showed that the average values of h_b were 3.25 to 3.63 kcal g^{-1}-COD-removed for the artificial wastewater. The values of true growth yield (Y_0) were 0.08 to 0.19 mg-MLSS mg^{-1}-COD for the food-processing wastewater at different temperatures. The COD removal efficiency was 77 to 91%, and it was decreased as temperature increased. But, the oil and grease (O and G) removal efficiency was 50 to 69%, and increased as temperature increased. These results might indicate that oil and grease become more soluble and accessible to microorganisms at high temperatures. The study indicated the temperature effect constant (∅) of van't Hoff-Arrhenius law was 0.958, which explained and showed typical characteristics in the low sludge yield of an ATAT process.*

Key words: *ATAT system; Temperature effect; Biological heat potential, Growth yield, Oily wastewater*
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Introduction

Thermophilic aerobic treatment process has conspicuous advantages as compared with the activated sludge process (ASP) the high degradation rate and low microbial growth yield due to Surucu *et al*. (1975, 1976) used a 273 liter reactor to evaluate kinetic parameters of the thermophiles at 58°C. The system heat balance and performance was successfully simulated by a model. The aerobic treatment of sewage sludge contaminated with difficult biodegradable organic substances such as 4-NP under thermophilic conditions has been proven successful (Fawzi *et al*., 2000). In thermophilic aerobic treatment of organic wastewaters high and stable COD removals have been investigated in laboratory and pilot-scale (Jahren *et al*., 2002; Suvilampi and Rintala, 2002; Vogelaar *et al*., 2002). Nevertheless, the major problems encountered are disappointing sludge settling characteristics in thermophilic aerobic biological treatment system (Carter and Barry, 1975).

ATAT system was operated at high organic loadings, the reactor was capable of maintaining high temperature with spontaneous reaction without external heat addition (LaPara and Alleman, 1999). Recently, Chiang *et al*. (2001) demonstrated that the biological heat contributed 50 to 55% as the total heat in a biological reactor. In Taiwan, the ATAT process in canned food wastewater has the h_b value as 4.72 kcal g^{-1} COD-removed that calculates by heat flux balance model. Hung *et al.* (2008) reported the specific biological heat potential (h_b) for full-scale practical and artificial wastewaters were 3.7 kcal g^{-1} COD (Yo = 0.1 mg MLSS mg^{-1} COD) and 3.1 kca l g^{-1} COD (Yo = 0.13 mg MLSS mg^{-1} COD). Furthermore, the results have also been established by Juteau *et al*. (2004) by using a self-heating aerobic thermophilic sequencing batch reactor (AT-SBR) to treat swine waste. LaPara and Alleman (1999) conducted an in-depth review of autothermal thermophilic aerobic treatment (ATAT) for wastewater. They concluded that the ATAT process had similar advantages as for the ATAD (autothermal thermophilic aerobic digestion) process. The system is capable of high-strength wastewater treatment, such as pulp and paper, livestock, and food-processing wastewaters.

Although the ATAT system has many advantages, but the applications in full-scale wastewaters treatment were relatively few, because of the lack of fundamental understanding for the engineering design, especially the biological heat potential of wastewater. Also, many system parameters were important and want to be studied for process design and the evacuation of system performance, such as the prediction of spontaneous reaction, kinetic constants, cell yield, oxygen transfer factors and temperature effect. In this study, the biological heat potential and temperature effect of an ATAT system were studied with a batch reactor.

Materials and Methods

Source of microorganisms: Microbe samples were obtained from a full-scale ATAT system for food processing wastewater treatment in Taiwan. The system was used to treat the oil and grease wastewater discharged from a chicken chunk producing company. The values of pH and temperature were in the range of 6.1~6.5 and 45~55°C,

Table - 1: The operation conditions of tested ATAT system

	35°C	45°C	55°C	65°C
Influent temperature (°C)	35	45	55	65
Operation time (day)	30	30	30	30
Eeactor volume (l)	1.8	1.8	1.8	1.8
SRT (day)	15	15	15	15
Initial MLVSS (mg l^{-1})	2762	2762	2762	2762
$S_{i,COD}$* (mg l^{-1})	21460	21460	21460	21460
$S_{i,oil}$** (mg l^{-1})	1000	1000	1000	1000
F/M (mg-COD mg^{-1} MLVSS)	0.52	0.52	0.52	0.52

*$S_{i,COD}$: influent COD, **$S_{i,oil}$: influent O and G

respectively. The COD removal was as high as 95% at the volumetric COD loading of 4.1 kg $m^{-3}d^{-1}$. (Chiang *et al.*, 2001).

Performance analysis: The analysis including of COD, BOD_5, oil and grease (O and G), suspended solids, and volatile suspended solids (VSS) were conducted following Standard Methods (APHA, 1998). The open-reflux dichromate method was used for COD analyses. The enriched culture dilution method was used for BOD analyses. The hexane extraction method was used for oil and grease analyses. Solids analyses were performed at 103-105°C for SS and 550°C for VSS. Oxygen uptake rate (OUR) was determined by DO meter in BOD bottles for the mixed liquid suspended solids from the thermophilic reactor. Samples were taken for analyses twice per day during the experimental period. The measure of lipase activities was in accordance with Wang and Chen (1998).

Incubation: The artificial wastewater contained 8.0 g l^{-1} glucose, 8.0 g l^{-1} glutamate and 1 g l^{-1} olive oil. Besides, according the measured COD, N and P were added at the ratio of 100: 5: 1 to supply the required nutrients and trace elements. The temperature was controlled at 35, 45, 55 and 65°C for the incubating process. The sludge retention time (SRT) was controlled at 15 days.

The incubation system consisted of seven major components (Fig.1): an ATAT reaction vessel (1.8 liter), stirrer (500 rpm), aerator (3 liter-air min^{-1}), heat supply system (19.2 cal s^{-1}), peristaltic pump, signal record, and a processing computer system. The reaction vessel was built with a 2.0 liter glass vessel (diameter is 20 cm) and was insulated with a 2.0 cm polyurethane foam layer. The ATAT reaction vessel was equipped with thermocouple (80W, 100 V) and thermometer.

Heat balance model and specific biological heat potential: Three series of experiment were conducted. In the first series, the pure water test was used to estimate the reactor heat loss, stirring heat contribution, and aeration heat loss. In the second series, the seeded culture was initially acclimated at sludge retention time (SRT) of 15 days and the liquid temperature was controlled at 55°C with extra heat compensation for 30 days. In the third series, after acclimating to reach the steady state (SRT = HRT = 15 days), the reactor was operated at SRT of 15 days without extra heat compensation. The temperatures of reactor and effluent were recorded. The characteristics

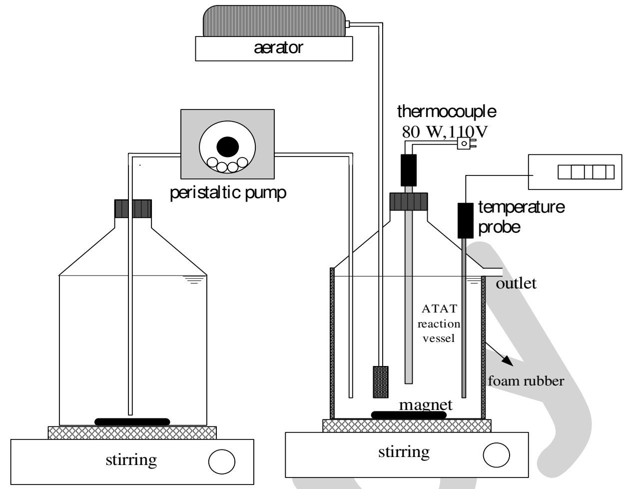

Fig. 1: Experimental set-up of the stirred-tank reactor continuously fed with substrates (Hung *et. al.*, 2008)

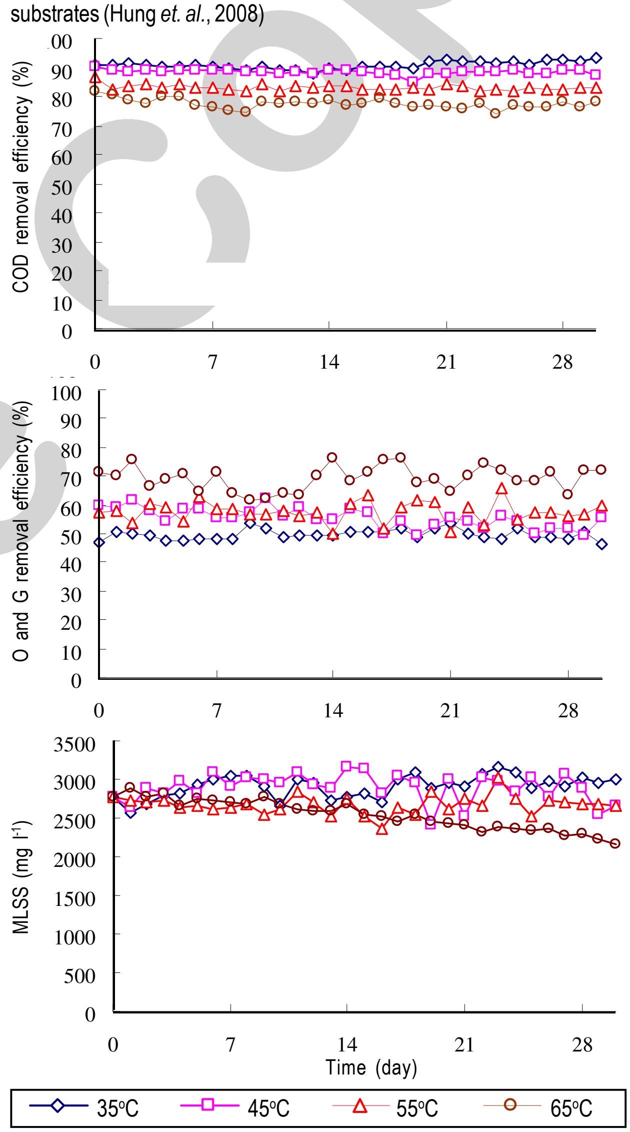

Fig. 2: Temporal variation of COD, O and G removal efficiencies and MLSS in ATAT reactors

Table - 2: Heat balance analysis for heat flux under different temperature conditions

	35°C		45°C		55°C		65°C	
	Mean	St-dev	Avge	St-dev	Mean	St-dev	Mean	St-dev
Tank temperature (°C)	32.5	0.4	43.3	0.3	52.3	0.3	59.2	0.3
MLSS (mg l^{-1})	3074.9	173.2	3053.3	199.3	2816.5	142.6	2677.5	222.0
MLVSS (mg l^{-1})	2911.7	144.0	2895.9	185.9	2666.2	119.0	2533.1	192.6
Effluent dissolve COD(mg l^{-1})	1972.7	291.5	2510.1	199.8	3654.9	158.5	4861.2	320.3
Effluent oil (mg l^{-1})	502.1	18.0	446.9	34.1	423.6	36.5	308.6	42.7
COD removal efficiency (E_{COD}, %) *	90.8	1.4	88.3	0.9	83.0	0.7	77.3	1.5
Oil removal efficiency (E_{oil}, %)	49.8	1.8	55.3	3.4	57.6	3.6	69.1	4.3
Substrates stream heat loss (Js, cal min^{-1})	0.21	0.04	0.14	0.02	0.22	0.02	0.49	0.03
Latent aeration heat loss (Ja, cal min^{-1})	873.0	-	873.0	-	873.0	-	873.0	-
Tank heat loss (Jt, cal min^{-1})	283.5	-	283.5	-	283.5	-	283.5	-
Thermocouple heat flux (J_h, cal min^{-1})	1152.0	-	1152.0	-	1152.0	-	1152.0	-
Biological reaction heat (J_b, cal min^{-1})	4.29	0.04	4.36	0.02	4.28	0.02	4.01	0.03
True growth yield (Y_0)**	0.27	0.01	0.22	0.03	0.11	0.02	0.24	0.02
Specific biological heat potential (h_b)***	3.63	0.08	3.55	0.15	3.25	0.09	3.84	0.06

* E_{COD}: [inf COD – eff COD]/ (inf COD) × 100% ; ** Y_0 : base on mg-MLSS(as COD) per mg-COD removed ; ***Calculation $h_b = J_b / [Q(S_{i,COD} \times E_{COD}(1-Y_0)]$, cal min^{-1}

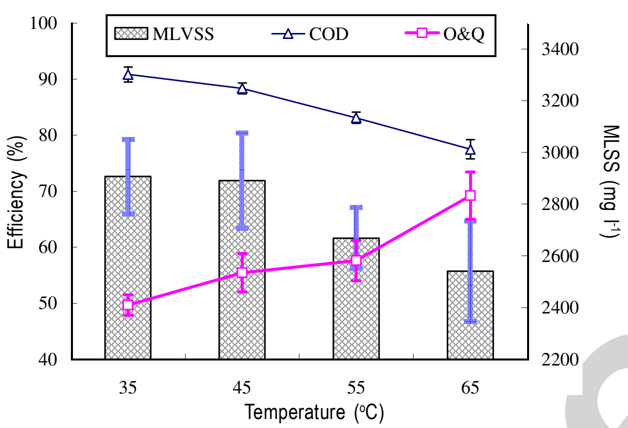

Fig. 3: The variations of COD, O and G removal efficiencies, MLSS at different temperature

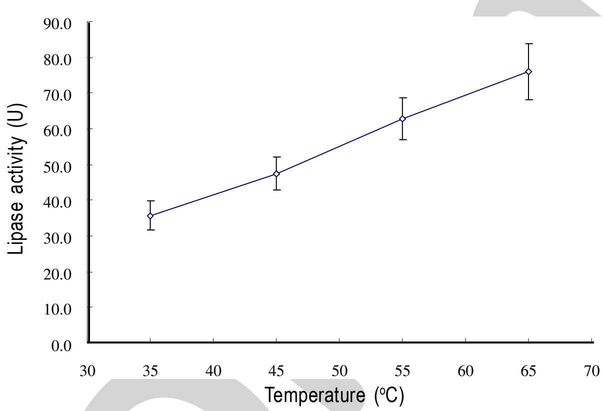

Fig. 4: The variation of lipase activity variation at different temperatures

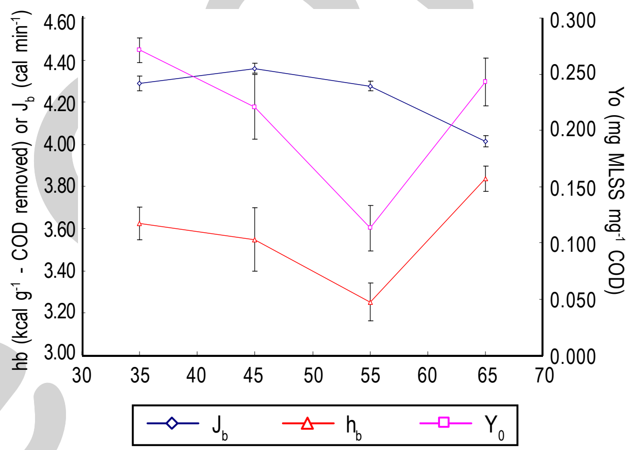

Fig. 5: The variation of Y_0, J_b and h_b at different temperatures

and operating of the reactors conditions were listed in Table 1.

The evaluation of h_b for the laboratory scale ATAT system was processed by a mathematical model. Chiang *et al.* (2001) used the heat flux (J) concept for the evaluation of h_b and defined J (cal min^{-1}) as the ATAT system control parameter. The experimental design was based on the simplification of the model (Hung *et al.*, 2008). The major difference between the Chiang's and the simplified models was gas latent heat rate. The measured value of gas heat flux by aeration was included gas latent heat rate. Therefore, the estimation of thermocouple heat flux (J_h) becomes more critical. The J_h must be lower than the heat requirement $[(J_w - J_{w1}) + (J_a - J_{a1}) + (J_t)]$. Therefore, the governing equation can be expressed as follows:

Accumulation heat flux (J_{acc}) = [Influent WW heat flux (J_w) – Effluent WW heat flux (J_{w1})] + [Inlet gas sensible heat flux (J_a) – Exit gas heat flux (J_{a1})] + [Reaction heat flux (J_b) – Reactor tank heat loss flux (J_t)]. In other words,

$$J_{acc} = [(J_w - J_{w1}) + (J_a - J_{a1}) + (J_b) - (J_t)] \quad (1)$$

The temperature effect: Temperature is an important parameter in the ATAT system, because temperature could affect the oxygen solubility in wastewater and affect the biodegradable rate. Basically, the temperature effect on the reaction rate constants can be estimated by the Van't Hoff-Arrhenius equation (Tchobanoglous *et al.,* 2003).

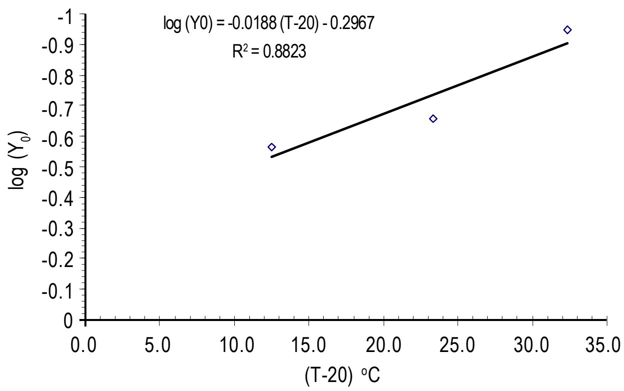

Fig. 6: The logarithm value of true growth yield and temperature regression analysis

$$K_T = K_{20}\varnothing^{(T-20)} \qquad (2)$$

In other words,

$$\text{Log}\ (\boldsymbol{K_T}) = \log(K_{20})+(T\text{-}20)\ \log(\varnothing) \qquad (3)$$

The K_{20} was known as the reaction rate constant at 20°C, the K_T was the reaction rate constant at T°C. In this study, the reaction rate constant is true growth yield (Y_0). The $\varnothing$ value was a temperature coefficient constant value of Van't Hoff-Arrhenius equation.

Results and Discussion

System performance and operation parameters: Fig. 2 showed daily effluent COD, O and G and mixed liquid of vaporized suspended solid (MLVSS) in the ATAT efficiencies during experimental period. The average influent COD concentration of the artificial waste-water was 21460 mg l^{-1}. The system was fed with artificial wastewater after acclimation. The system was operated at 35, 45, 55 and 65°C with external heat. Table 2 gives daily average of the treatment performance during experimental period. The COD removal efficiencies of the artificial wastewater were in the range of 77 to 91%. Because the substrates of the artificial wastewater were readily biodegradable, COD removal was relatively significant. However, an increase in the operating temperature decreased COD removal efficiencies. The lower yield of microorganisms (lower MLSS) at the higher temperature might result in the decrease of COD removal. This phenomenon might result in an underestimate of E_{COD} and overestimate of Y_0.

Table 2 shows the Y_0 and h_b values in this study. The average Y_0 was 0.27, 0.22, 0.11 and 0.24 mg-MLSS (as COD) mg^{-1}-COD removed at 35, 45, 55, and 65°C, respectively. Assume the equivalent value was 1.42 g COD of per g MLSS, the Y_0 values could be expressed as 0.19, 0.15, 0.08 and 0.17 mg-MLSS mg^{-1} COD removed, which were only about 1/3 of that in the traditional activated sludge process (Tchobanoglous *et al.,* 2003).

Figure 3 showed mean COD and O and G removal efficiencies at different temperatures during this study. The COD and O and G removal efficiencies could reach 91±1.4% and 69±4.3%, respectively. Fig. 3 and Fig. 4 also shows that the COD removal efficiency and MLSS decreased as temperatures increased. But, the O and G removal efficiency and lipase activity increased as temperature increased. The reactor were operated above the melting temperature of oil and grease, these substances become more accessible to microorganisms and their lipolytic enzymes. Therefore, an increase in operating temperature also increased O and G removal efficiencies. The result demonstrated that ATAT system could be employed to treat the high-strength oily wastewater.

Evaluation of the specific biological heat potential: In the study, we employed the heat balance model to evaluate the reaction spontaneity. The heat balance model was in accordance with Hung *et al.* (2008). The true growth yield (Y_0) could be defined as following equation:

$$Y_0 = X_{t,COD} /(\ S_{i,COD}\ \times E_{COD}) \qquad (4)$$

In the model, the net gas sensible heat rate and tank heat loss rate were measured by background test in reactor without the supply of substrate and by the aeration heat loss, respectively.

According to the equation 1, we could employ the test reactor heat loss, stirring heat contribution (J_l), and aeration heat loss (J_a– J_{a1}) to calculate the J_b value under steady state. Then, the J_b and equation 4 could be used to monitor the daily effluent temperature, effluent COD concentrations, and MLVSS concentrations every day. These results could be then used to calculate the h_b value. Table 2 shown J_b values which were greater than zero. It means the reaction was spontaneity in the ATAT system. Fig. 5 shows that Y_0, J_b, and h_b decreased gradually at 55°C. But, the h_b and Y_0 values decreased as the temperature increased. However, these values increased again as the temperature reached 65°C due to substantially decaying in biomass as temperature reached 65°C. The decaying biomass (MLSS) was then transformed to form the aqueous COD present in the effluent that resulted in an overestimation of Y_0 and h_b values. Furthermore, the true growth yield and specific biological heat potential decreased as temperature increased. These results showed the reduction energy from the substrates run into energy pathway instead of the cell synthesis pathway at high temperatures with the bioenergetics viewpoint (McCarty, 1971).

Estimation of temperature effect ($\varnothing$) on the true growth yield (Y_0): According to Table 2 results, we could model the relationship between Y_0 and temperature with equation 3. The Y_0 is a reaction rate constant in equation 3. Fig. 6 shows the result of regression analysis. The regression equation is:

$$\text{Log}\ (K_T) = -0.0188(T\text{-}20) - 0.2967 \quad (R^2 = 0.8823) \qquad (5)$$

On here, the correlation coefficient is 0.8823, which mean fine correlate. The value of log (K_{20}) is -0.2967, it means the K_{20} is 0.505 and the value of log($\varnothing$) is -0.0188. These result suggested that the $\varnothing$ value is 0.958. The obtained $\varnothing$ value is less than 1.0 and lower than that suggested by Tchobanoglous *et al.* (2003). The reported $\varnothing$ value was about 1.02 to 1.1, and the typical value was 1.04 for the active sludge system. The result explained and showed the typical characteristics of ATAT process, such as the low sludge yield. But, the obtained K_{20} was

0.505 in the study; it suggested that the true growth yield was 0.505 mg-COD mg^{-1}-COD removed at 20°C. Then, the Y_0 could be expressed as 0.36 mg-MLVSS mg^{-1}-COD removed, this is a reasonable value of conventional activated sludge process at 20°C.

In this study, the J_b values were greater than zero; it means the reaction was spontaneous in the ATAT system. The highest COD and O and G removal efficiencies were 91±1.4% and 69±4.3%, respectively. These result demonstrated that, with proper design, the ATAT system could effectually treat the high-strength oily wastewaters. The concentrations of MLVSS gradually decreased as the operating temperature increased. However, temperature variation did not affect O and G removal efficiency, because lipase activity is heat-resistant. Also, high temperature increased the solubility of O and G resulting in a better availability.

The result showed that The Y_0 was 0.19, 0.15, 0.08, and 0.17 mg-MLSSm g^{-1}-COD removed at 35, 45, 55, and 65°C, respectively. Y_0, J_b, and h_b decreased gradually at 55°C. However, the Y_0 and h_b values significantly increased at 65°C, because the soluble COD increased at high temperatures. And it means the ATAT system was not proper to operate more high temperature. Although, the lipase active was to increase as operate temperature, but the obtained $\varnothing$ value is 0.958 suggested that the concentrations of biomass decreased as temperature increased. So, the biomass stability was more important in the ATAT system. These Y_0 values were only about 1/3 of that in the conventional activated sludge process at 55°C. The study results clearly explained and showed typical characteristics of ATAT process, such as low sludge yield.

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References

APHA: Standards Methods for examination of water and wastewater. 20th Edn. APHA, AWWA, WPCF, Washington DC, USA (1998).

Carter, J.L. and W.F. Barry: Effects of shocks temperature in biological systems. *J. Environ. Eng. Div. Am. Soc. Civ. Eng.*, **101**, 229-243 (1975).

Chiang, C.F., C.J. Lu, L.K. Sung and Y.S. Wu: Full-scale evaluation of heat balance for autothermal thermophilic aerobic treatment of food processing wastewater. *Water Sci. Technol.*, **43**, 251-258 (2001).

Fawzi, A. Banat, Prechtl, Stephan and Bischof, Franz: Aerobic thermophilic treatment of sewage sludge contaminated with 4-nonylphenol. *Chemosphere*, **41**, 297-302 (2000).

Hung, J.M., C.Y. Chen, Y.S. Wu and C.J. Lu: Evaluation of specific biological heat potential of oily wastewater in an autothermal thermophilic aerobic treatment system. *J. Environ. Biol.*, **29**, 655-660 (2008).

Jahren, S., J. Rintala and H. Odegaard: Aerobic moving bed biofilm reactor treating thermomechanical pulping (TMP) whitewater under thermophilic conditions. *Water. Res.*, **36**, 1067-1075 (2002).

Juteau, P., D. Tremblay, C.B. Ould-Moulaye, J.G. Bisaillon and R. Beaudet: Swine waste treatment by self-heating aerobic thermophilic bioreactors. *Water Res.*, **38**, 539-546 (2004).

LaPara, T.M. and J. E. Alleman: Thermophilic aerobic biological wastewater treatment. *Water Res.*, **33**, 895-908 (1999).

McCarty, P.L.: Energetics and bacterial growth. *In*: Organic compounds in aquatic environments (*Eds.*: S.D. Faust and J.V. Hunter). Marcel Dekker, Inc., N.Y. (1971).

Surucu, M.H., E.S.K. Chian and R.S. Engelbrecht: Thermophilic microbiological treatment of high strength wastewaters with simultaneous recovery of single cell protein. *Biotechnol Bioengineering*, **17**, 1639-1662 (1975).

Surucu, M.H., E.S.K. Chian and R.S. Engelbrecht: Aerobic thermophilic treatment of high strength wastewaters, *Journal Water Pollution Cont. Fed.*, **48**, 669-679 (1976).

Suvilampi, J. and J. Rintala: Comparison of activated sludge processes at different temperatures: 35°C, 27–55°C and 55°C. *Environ. Technol.*, **23**, 1127-1134 (2002).

Tchobanoglous, G., F.L. Burton, H.D. Stensel: Wastewater Engineering, Treatment and Reuse, 4th Edn., Metcalf and Eddy. Inc. McGraw-Hill Company (2003).

Vogelaar, J., E. Bouwhuis, A. Klapwijk, H. Spanjers and J. Van Lier: Mesophilic and thermophilic activated sludge post-treatment of paper mill process water. *Water Res.*, **36**, 1869-1879 (2002).

Wang, T.J. and T.L. Chen: Lipase production by Acinetobacter radioresistens in a batch fill-and-draw culture. *Appl. Biochem. Biotechnol.*, **73**, 185-194 (1998).