Performance of an Anaerobic Baffled Reactor (ABR) during start-up period

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***Abstract*—**appropriate start-up of an anaerobic baffled reactor (ABR) is considered to be the most delicate and important issue in the anaerobic process, and depends on several factors such as wastewater composition, reactor configuration, inoculum and operating conditions. In this work, the start-up performance of an ABR with working volume of 30 liters, fed continuously with synthetic food industrial wastewater along with semi-batch study to measure the methangenic activity by specific methanogenic activity (SMA) test were carried out at various organic loading rates (OLRs) to determine the best OLR used to start up the reactor. The comparison was based on COD removal efficiencies, start-up time, pH stability and methane production. An OLR of 1.8 Kg COD/m3d (5400 gCOD/m3 and 3 days HRT) showed best overall performance with COD removal efficiency of 94.44% after four days from the feeding and methane production of 3802 ml/L with an overall SMA of 0.36 gCH4-COD/gVS.d

***Keywords*—**Anaerobic baffled reactor, Anaerobic reactor start-up, Food industrial wastewater, Specific methanogenic activity.

I. Introduction

Whenever and wherever food, in any form, is handled, processed, packed and stored, there will always be an unavoidable generation of wastewater. Most of the volume of wastewater comes from cleaning operations at almost every stage of food processing and transportation operations. The quantity and general quality (i.e., pollutant strength, nature of constituents) of this processing wastewater generated have both economic and environmental consequences with respect to its treatability and disposal [1] [2].

In contrast to domestic wastes, food industrial effluents pose many problems for treatment, and such effluents are subjected to daily, and sometimes seasonal, fluctuations with respect to both their flow and strength. In most cases it has been found that biological processes are more economic and efficient than physical/chemical treatment [3].

Over the past thirty years there has been an increasing demand for more efficient systems for the treatment of wastewaters due to increasingly stringent discharge standards now widely adopted by various national and international agencies. Anaerobic treatment has proven over recent years to be a better alternative to aerobic processes, especially for the treatment of high strength wastewaters [4]. It could be a cost-effective solution to many challenges facing the industry today: rising energy costs, high sludge disposal costs and tighter effluent limitations. Properly designed anaerobic treatment systems have the potential to provide a renewable energy source (biogas), consume less energy and generate less sludge.

In recent years, anaerobic technology has been applied to the treatment of many medium and high-strength industrial wastewaters [5].

The anaerobic baffled reactor (ABR) is one of these high-rate anaerobic designs developed by McCarty and co-workers at Stanford University [6]. It is suggested by several researchers as a promising system for industrial wastewater treatment [7] [8] [9] [10]. The ABR has been described as a series of USABs which does not require granulation for its operation. Therefore, it has lower start-up period than the other high rate reactors [11]. The ABR uses a series of vertical baffles to force the wastewater to flow under and over them as it passes from inlet to outlet, the wastewater can come into intimate contact with a large amount of active biomass, while the effluent remains relatively free of biological solids [12] [13]. Moreover, the ABR features in separating acidogenesis and methanogenesis longitudinally down the reactor and enhancing reactor stability [14].

Prompt start-up is essential for the highly efficient operation of ABR, due to slow growth rates of anaerobic microorganisms, especially methane producing bacteria (MPBs) [14]. During anaerobic reactor start-up, the biomass is acclimatized to new environmental conditions, such as substrate, operating strategies, temperature and reactor configuration [15].

Potential problems can arise during reactor start-up as a result of the accumulation of volatile fatty acids (VFAs) and dissolved H2 which occurs when the methanogens and certain acetogens are greatly outnumbered by the fast growing acidogens [16]. Low pH and the exposure of the sensitive bacteria in front compartments of the ABR to toxic levels of inorganic and organic compounds in the feed can be considered to be of the start-up problems.

The reduction of the period necessary for the start-up and improved operational control of the anaerobic processes are

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important factors to increase the efficiency and the competitiveness of the high-rate anaerobic systems [17].

In this study, feeding wastewater with only soluble organics was used while keeping the reactor temperature in the range for methanogens growth (35°C) in order to obtain shorter start-up time. Then a continuous study on the ABR treatment performance during the start-up along with semi-batch study to measure the methanogenic activity by specific methanogenic activity (SMA) test were carried out to control the initial organic loading rate thus giving a more reliable start-up of the ABR with a convenient OLR.

II. METHODS

A. ABR Configuration

A laboratory scale ABR was rectangular box fabricated using transparent Perspex sheets, with internal dimensions of 50 cm in length, 24 cm in width and a depth of 30 cm, and a working reactor volume of 30 liters. As shown in Fig. 1, the ABR was divided into five equal rectangular compartments by vertical standing baffles. Each compartment was further divided into two parts by a vertical hanging baffle which created down comer and up comer regions. The width of the down-comer and up-comer were 2 cm and 8 cm, respectively. The lower portions of the hanging baffles were bent 3 cm above the reactor's base at a 45º angle to direct the flow evenly through the up-comer. The liquid flow is alternatively upwards and downwards between compartment partitions. This produced effective mixing and contact between the wastewater and biosolids at the base of each up-comer. Sampling ports were located in the middle of the top of each compartment allowing drawing biological sludge, and liquid samples. A variable speed peristaltic pump (Masterflex L/S) was used to control feed rate. To maintain anaerobic conditions, the sampling ports of the reactor and the fittings were sealed after inoculation. The reactor was maintained at 35º C using a 50 watts aquarium heater in each compartment.

B. SMA test equipment

SMA test was conducted in 250 ml working volume serum bottles formed three sets (1.2, 1.8 & 2.0 kgCOD/m^3d) at 35 °C under anaerobic conditions. Serum bottles were filled with applied grams of glucose-COD and 20 gVSS/L of biomass but the decay bottle was filled with tap water and 20 gVSS/L of biomass to represent the methane production due to cell decay. Four successive feedings were made for each set. At the end of the first feeding, the liquid media were carefully decanted and fed to the subsequent bottles while the sludge in the first bottles was again exposed to the synthetic wastewater, and so on. The total gas production was recorded and collected at intervals of 20, 40, 60, 80, 100 and 120 hours after the start. Specific methanogenic activity was calculated from the total methane production through 5 days.

C. Wastewater and Seeding Materials

The reactor was fed with synthetic wastewater containing glucose as a carbon source. The synthetic feed was composed of glucose ($C_6H_{12}O_6$), di-ammonium hydrogen phosphate ($(NH_4)_2HPO_4$), ammonium chloride (NH_4CL) and di-potassium hydrogen ortho-phosphate (K_2HPO_4). It was made up freshly every day by diluting the stock with tap water to achieve the total COD concentration required for each loading rate. Trace metals were added at the beginning of the startup period of the reactor to favor bacterial growth. The compositions of these elements (in mg/l) were as follows: $FeCl_3$, 5.0; $CuSO_4.5H_2O$, 5.0; $MgSO_4.7H_2O$, 39.0; $MnSO_4.4H_2O$, 13.9; $CaCl_2.2H_2O$, 36.8 [18]. In order to prevent the build-up of a localized acid zone in the reactor, sodium bicarbonate was used for supplementing the alkalinity. The reactor and the serum bottles were seeded with anaerobically digested sludge taken from an anaerobic digester at the Egyptian Starch Yeast & Detergents Company (ESYD). It was first sieved (<3mm) to remove any debris and large particles and was then introduced uniformly into all five compartments, so that each compartment was filled with 32% sludge with a concentration of solids of 88.7 g SS/L and 64.7 g VSS/L, giving a total of 600 g VSS in the reactor. This value (20 g VSS/L of reactor volume) agreed with the initial VSS values used in other studies undertaken on ABRs [19].

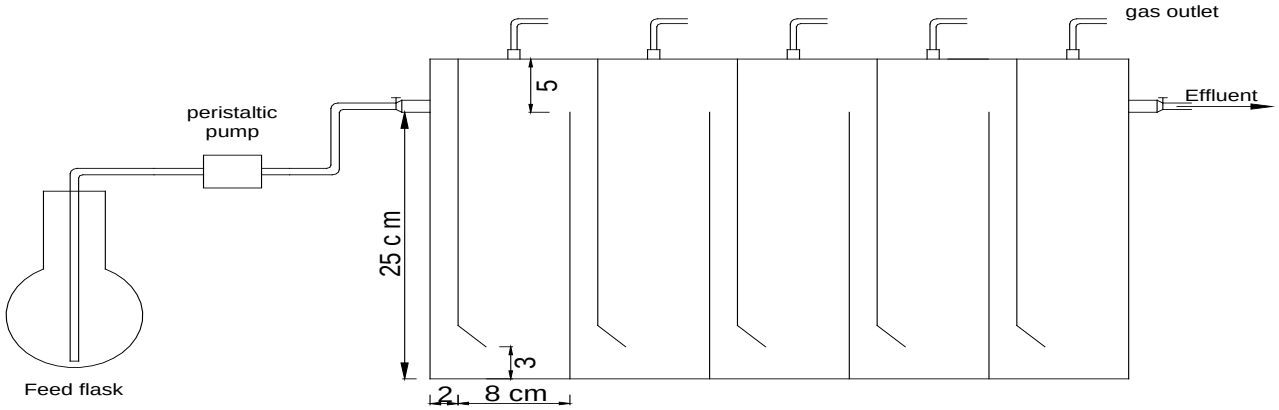

Fig. 1 Schematic diagram of lab scale anaerobic baffled reactor

D.Analytical Methods

The total gas production was measured by passing it through a liquid containing 2% (v/v) H2SO4 and 10% (w/v) NaCl while methane gas was detected by using a liquid containing 3% NaOH to scrub out the carbon dioxide from the biogas [20]. The methanogenic activity, AC_m (g CH_4-COD/g VSS·d), was determined according to Campos [21] as follows:

$$AC_m = \frac{R}{f \,.V\,.[VSS]} \quad (1)$$

Where: R, methane production rate (mL CH_4/d), f is the conversion factor from CH_4 to g COD (350 mL CH_4/g COD for normal condition), V is the liquid phase volume and [VSS] is the biomass concentration (g/L). pH were measured daily with a calibrated pH-meter (Digital pH/ mV/ ORP meter kit). COD was determined according to Standard Methods for the Examination of Water and Wastewater [22].

III. Results And Discussion

A. Continuous Study

Despite the recommended initial loading rate for anaerobic treatment is approximately 1.2 KgCOD/m^3d, the 1.8 KgCOD/m^3d showed best reactor performance and stability in terms of COD removal efficiency and startup duration. Table I shows the COD removal efficiencies based on organic loading rate. When starting with an OLR of 1.2 KgCOD/m^3d (3600 mgCOD/l), the reactor removed 94.17% of COD after 17 days while removed 94.94 % of COD after 7 days of feeding with a COD concentration of 9000 mg/l. A COD removal of 94.44 % was achieved after 4 days of reactor feeding with 5400 mgCOD/l (OLR of 1.8 KgCOD/m^3d) and a COD removal of 98.89% after 5 more days with a feeding of 9000 mgCOD/l. The third attempt considered higher initial organic loading rate (2.0 KgCOD/m^3d) corresponding to 6000 mgCOD/l. It took 6 days to reach a steady COD removal of 92.67% which was less than the previous attempts by about 1.6%, but after 8 days of 9000 mgCOD/l feeding; 97 % of COD was removed. All the attempts showed an increase in COD removal efficiencies during the very first start-up except for the first run; the removal efficiency decreased with a sudden influent pH decrease, but went up after only two days. The best performance was observed with an OLR of 1.8 kgCOD/m^3d (94.44% after 4 days).

B. Semi-Batch Study

The SMA test was carried out through one week for all the organic loading sets. AC_m values were calculated according to (1). The results are shown in Fig. 2. In the first vials, the maximum specific methanogenic activity values were, at the end of the first 20 hours of the test, 0.15 g CH_4-COD/gVS.d at OLR of 1.8 kgCOD/m^3d. Then the values declined, perhaps as a result of the increase production of VFAs accompanied with a drop in pH values which inhibited methane production. An increase in SMA at OLR of 1.2 kgCOD/m^3d was observed after 80 hours from the beginning of the experiment comparing with the others and that may be due to the lower COD concentration which encouraged acclimation of the methanogens faster. That is why SMA values of OLR of 1.2 kgCOD/m^3d were higher in the second and fifth vials. In contrary, in the third vial sets SMA values reached 0.4 – 0.45 g CH_4-COD/gVS.d after 80 hours at OLRs of 1.8 and 2.0 kgCOD/m3d, respectively and that were consistent with the results of Martin J. *et al.* [23]. The SMA values reached their maximum values in the fifth vials OLRs of 1.2 and 1.8 kgCOD/m^3d. The maximum value was 0.85 g CH_4-COD/gVS.d at OLR of 1.2kgCOD/m^3d which is in agreement with the ranges of methanogenic activity for acetate substrate reported by [24] [25] [21] [26] [27]. SMA values from the decay vials were around 0.05 g CH_4-COD/gVS.d. It was obviously noted that after 60 hours, the methanogenic activities increased along the vials reached their maximum values in the later vials which revealed partial phase separation.

Fig. 3 presents average overall values of SMA during the entire experiment time which revealed that at a constant HRT of 3 days and constant VSS in all sets, average overall SMA values decreased with the increase of influent COD. The values at OLRs of 1.2, 1.8 and 2.0 KgCOD/m^3d were 0.46, 0.36 and 0.31 g CH_4-COD/gVS.d, respectively. Previous studies reported SMA values observed in various industrial and laboratory digesters that ranged between 0.1 and 1.0 g CH_4-COD/gVS.d [28]. It should be noted, however that the SMA test only measures the methane production from acetic acid, generally referred to as the acetoclastic methanogenic activity and does not include methane produced by hydrogen utilizing methanogic bacteria [29].

Table II shows average pH values in the test bottles. pH values in the first bottles in all sets were below 6.0. That can be attributed to the fact that high concentrations of volatile fatty acids (VFAs) were present in these bottles, while in later bottles due to conversion and stabilization of intermediate products i.e. VFAs to methane and activity of methanogenic bacteria the pH values increased to neutral range [30]. It was observed that pH values in third, fourth and fifth bottles of the third sets were high comparing with the others. The most likely explanation for this observation is the formation of HCO_3^- due to the reaction of OH^- with CO_2 produced during anaerobic degradation [11].

Considering only SMA test results, OLR of 1.2 showed methanodenic activities greater than those of OLRs of 1.8 and 2.0 kgCOD/m^3d. However, at steady state, OLR of 1.8 kgCOD/m^3d achieved an excellent organic matter removal, i.e. 94.44% COD removal after only 4 days of 5400 mgCOD /L feed strength and 98.8% COD removal after 5 days of 9000 mgCOD /L feed strength.

TABLE I
RESULTS OF THREE DIFFERENT INITIAL OLRS

Run I	3600 mgCOD/l (1.2 kgCOD/m^3d)	Time(day)	1	13	15	17	18	34
		COD_{rem} (%)	89	88.56	89.94	94.17	94.17	94.94
Run II	5400 mgCOD/l (1.8 kgCOD/m^3d)	Time(day)	1	3	4	5	15	16
		COD_{rem} (%)	90	90.2	94.44	94.44	98.89	98.6
Run III	6000 mgCOD/l (2.0 kgCOD/m^3d)	Time(day)	1	3	6	7	25	26
		COD_{rem} (%)	81	81.33	92.67	92.67	97.78	96.9

At 9000 mgCOD/l – OLR of 3.0 KgCOD/m^3.d

TABLE II
PH RESULTS OF THE THREE DIFFERENT INITIAL OLRS

Run I	3600 mgCOD/l (1.2 kgCOD/m^3d)	Bottle	1	2	3	4	5
		pH	5.02 ± 0.17	6.55 ± 0.20	7.05 ± 0.16	7.19 ± 0.53	7.39 ± 0.20
Run II	5400 mgCOD/l (1.8 kgCOD/m^3d)	Bottle	1	2	3	4	5
		pH	4.67 ± 0.44	6.46 ± 0.12	7.06 ± 0.42	7.03 ± 0.53	7.22 ± 0.26
Run III	6000 mgCOD/l (2.0 kgCOD/m^3d)	Bottle	1	2	3	4	5
		pH	4.60 ± 0.62	6.21 ± 0.29	7.08 ± 0.61	7.20 ± 0.41	7.33 ± 0.07

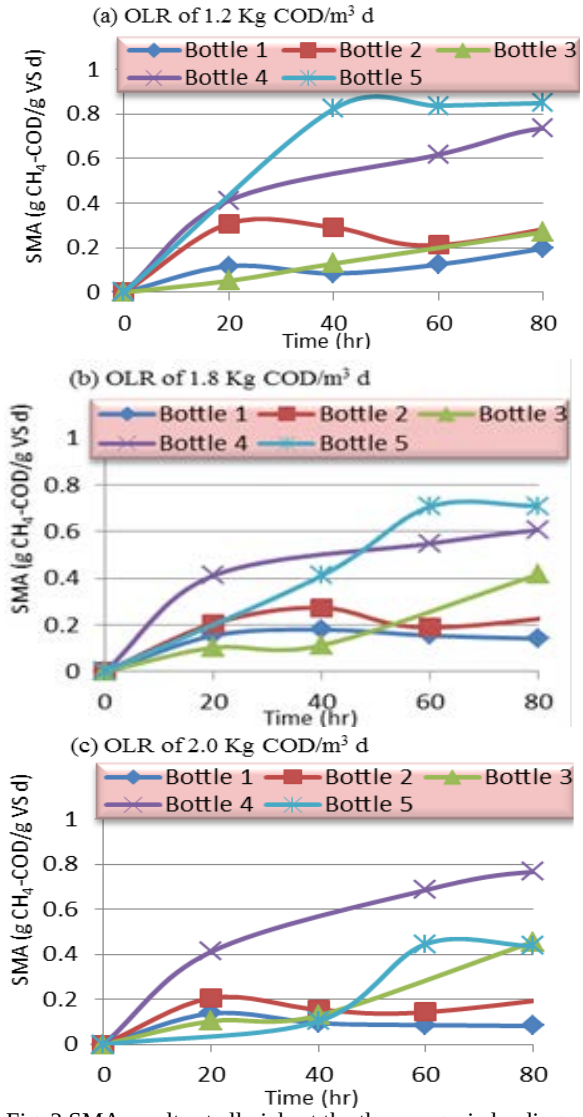

Fig. 2 SMA results at all vials at the three organic loading rates

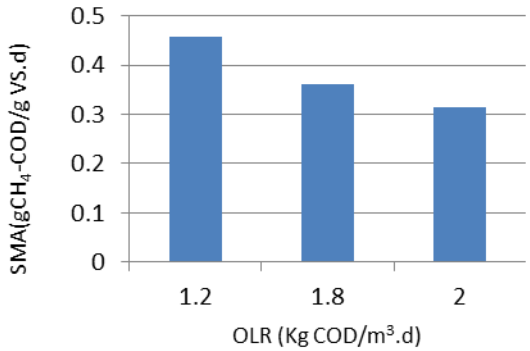

Fig. 3 Overall SMA values for OLRs 1.2, 1.8 & 2.0 KgCOD/m^3d after 120 hours from the start

IV. CONCLUSION

As has been said, start-up is often considered to be the most unstable and difficult phase in anaerobic process.

Based on the observations and the results obtained from the experimental studies the following points were concluded:

1) Increasing the initial OLR enhanced the biological oxidation up to a certain point at which OLR started to inhibit the degradation rate.
2) Startup the ABR with OLR of 1.8 KgCOD/m^3d (5400 mgCOD/l & 3 d HRT) showed best COD removal efficiencies and startup period (94.44% after 4 days) comparing with OLR of 1.2 and 2.0 KgCOD/m^3d which gave 94.17% COD removal efficiency after 17 d and 92.67% COD removal efficiency after 6 d, respectively.
3) The reactor started up with 1.8 KgCOD/m^3d achieved stable conditions resulted in best organic matter removal, i.e. over 98% COD removal efficiency at an OLR of 3.0 KgCOD/m^3d after 5 days of feeding.
4) Methanogenic activity (AC_m) results indicated partial

phase separation with increases in the activity at the later vials.

5) A maximum AC_m value of 0.85 g CH_4-COD/g VSS·d was obtained from the fifth bottle in OLR of 1.2 KgCOD/m^3d set with an overall value of 0.46 g CH_4-COD/g VSS·d, while at 1.8 KgCOD/m^3d, 0.71 g CH_4-COD/g VSS·d was obtained from the fifth bottle in the set with an overall value of 0.36 g CH_4-COD/g VSS·d.

REFERENCES

[1] R. E. Carawan, J. V. Chambers, R. R. Zall, and R. H. Wilkowske, "Fruit and Vegetable Water and Wastewater Management," *Extension Special Report No. Am-18E*, North Carolina State University and Science and Education Adminstration-Exension USDA – Washington, D.C., 1979, pp. 15–31.

[2] X. L. Sean, "Food and Agricultural Wastewater Utilization and Treatment," 1st ed. USA: Blackwell Publishing, 2007, ch. 1.

[3] M. G. Roig, M. J. Martin-Rodriguez, J. M. Cachaza, L. Mendoza-Sanchez, and J. F. Kennedy, "Principles of biotechnological treatment of industrial wastes," *Crit. Rev. Biotechnol.*, vol. 13, pp. 99–116, 1993.

[4] J. C. Akunna, and M. Clark, "Performance of granular-bed anaerobic baffled reactor (GRABBR) treating whiskey distillery wastewater," *Bioresource Technology*, vol. 74, pp. 257–261, 2000.

[5] S. Ghaniyari-Benisa, A. Martínb, and R. Borjac, "Kinetic modelling and performance prediction of a hybrid anaerobic baffled reactor treating synthetic wastewater at mesophilic temperature," *Process Biochemistry*, vol. 45, pp. 1616–1623, 2010.

[6] A. Bachmann, V. L. Beard, and P. L. McCarty, "Comparison of fixed film reactors with a modified sludge blanket reactor," in *Proc. The First International Conference on Fixed Film Biological Processes*, vol. 2, pp. 1192–1211, 1983.

[7] A. Bachmann, V. L. Beard, and P. L. McCarty, "Performance characteristics of the anaerobic baffled reactor," *War. Res*, vol. 19, pp. 99–106, 1985.

[8] R. Boopathy, V. F. Larsen, and E. Senior, "Performance of Anaerobic Baffled Reactor (ABR) in treating distillery wastewater from a Scotch Whisky factory," *Biomass*, vol. 16, pp. 133–143, 1988.

[9] A. Grobicki, and D. C. Stuckey, "Performance of the anaerobic baffled reactor under steady-state and shock loading conditions," *Biotechnol. Bioengng*, vol. 37, pp. 344–355, 1991.

[10] T. Setiadi, Husaini, and A. Djajadiningrat, "Palm oil mill effluent treatment by anaerobic baffled reactors: Recycle effects and biokinetic parameters," *Water Science Technology*, vol. 34, pp. 59–66,1996.

[11] H. Movahedyan, A. Assadi and A. Parvaresh, "Performance evaluation of an anaerobic baffled reactor treating wheat flour starch industry wastewater," *Iran. J. Environ. Health. Sci. Eng.*, vol. 4, no. 2, pp. 77–84, 2007.

[12] J. Wang, H. Yongheng, and Z. Xuan, "Performance and characteristics of an anaerobic baffled reactor," *Bioresour. Technol.*, vol. 93, no. 2, pp. 205–208, 2004.

[13] G.V.T. Gopala Krishna, Pramod Kumar, and Pradeep Kumar, "Treatment of low-strength soluble wastewater using an anaerobic baffled reactor (ABR)," *Journal of Environmental Management*, vol. 90, pp. 166–176, 2009.

[14] R. R. Liu, Q. Tian, B. Yang, and J. H. Chen, "Hybrid anaerobic baffled reactor for treatment of desizing," wastewater. *Int. J. Environ. Sci. Tech.*, vol. 7, no. 1, pp. 111–118, 2010.

[15] R. Alkarimia, S. B. Mahat, A. Yuzir, M. Fadhil, and S. Chelliapan, "Performance of an innovative multi stage anaerobic reactor during start-up period," *African Journal of Biotechnology*, vol. 10, no. 54, pp. 11294–11302, Sep. 2011.

[16] D. Massé, L. V. A. Masse, and S. Bilodeau, "The start-up of anaerobic sequencing batch reactors at 20° C and 25° C for the treatment of slaughterhouse wastewater," *Chem. Technol. Biotechnol. J.*, vol. 76, pp. 393–400, 2001.

[17] C. Chernicharo, "Anaerobic Reactors," *Biological Wastewater Treatment Series*, vol. 4, UK: IWA Publishing, pp. 133–141,2007.

[18] G.V.T. Gopala Krishna, Pramod Kumar, and Pradeep Kumar, "Complex wastewater treatment using an anaerobic baffled reactor," *Environmental Progress*, vol. 26, no. 4, pp. 391–398, 2007.

[19] W. P. Barber, and D. C. Stuckey, "The use of the anaerobic baffled reactor (ABR) for wastewater treatment: A review," *Water Research.*, vol. 33, no. 7, pp. 1559–1578, 1999.

[20] S. Tuzun, "Anaerobic/aerobic sequential treatment of chloramphenicole and streptomycin antibiotics using anaerobic baffled and aerobic sludge reactors," *Msc. Thesis, Dokuz Eylül University*, 2009.

[21] E. Campos, M. Almirall, J. Mtnez-Almela, J. Palatsi, and X. Flotats, "Feasibility Study of the anaerobic digestion of dewatered pig slurry by means of polyacrylamide," *Bioresource Technology*, vol. 99, pp. 387–395, 2008.

[22] APHA AWWA, "Standard Methods for the Examination of Water and Wastewater," 20th ed. *American Public Health Association, Washington, DC.*, 1999.

[23] J. Martin, K. J. Kennedy, and C. Eskicioglu, "Characterization of an anaerobic baffled reactor treating dilute aircraft de-icing fluid and long term effects of operation on granular biomass," *Bioresource Technology*, vol. 101, pp. 2217–2223, 2010.

[24] C. J. Sandoval, M. V. Mendoza, M. Carreno, and E. F. Castillo, "Microbiological characterization and specific methanogenic activity of anaerobe sludges used in urban solid waste treatment," *Waste Management*, vol. 29, pp. 704–711, 2009.

[25] D.-Y. Cheong, and C. L. Hansen, "Effect of feeding strategy on the stability of anaerobic sequencing batch reactor responses to organic loading conditions," *Bioresource Technology*, vol. 99, pp. 5058–5068, 2008.

[26] Y. A. Oktem, O. Ince, P. Sallis, T. Donnelly, and B. K. Ince, "Anaerobic treatment of a chemical synthesis-based pharmaceutical wastewater in a hybrid upflow anaerobic sludge blanket reactor," *Bioresource Technology*, vol. 99, pp. 1089–1096, 2007.

[27] M. Hutnan, L. Mrafkova, M. Drtil, and J. Derco, "Methanogenic and Nonmethanogenic Activity of Granulated Sludge in Anaerobic Baffled Reactor," *Chem. Papers*, vol. 53, no. 6, pp. 374–378, 1999.

[28] N. Sinbuathong, S. Khaodhiar, W. Liengcharensit, P. Sirirote, and D. Watts, "Effect of sulfate on the methanogenic activity of a bacterial culture from a brewery wastewater during glucose degradation," *Environmental Science*, vol. 19, no. 9, pp. 1025–1027, 2007.

[29] O. Ince, K. Anderson, and B. Kasapgil, "Control of organic loading rate using the specific methnogenic activity test during start-up of an anaerobic digestion system," *Wat. Res.*, vol. 29, no. 1, pp. 349–355, 1995.

[30] S. Uyanik, P. J. Sallis, and G. K. Anderson, "The effect of polymer addition on granulation in an anaerobic baffled reactor (ABR). Part I: process performance," *Water Research*, vol. 36, pp. 933–943, 2002.