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Performance of an Anaerobic Baffled Reactor (ABR) Treating High-Strength Food Industrial Wastewater with Fluctuating pH

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***Abstract*—As awareness of the variable nature of food industrial wastewater and its environmental impact grows, a more stable treatment reactor is needed to treat such wastewater. In this paper, a performance of 5-compartment lab-scale Anaerobic Baffled Reactor (ABR) treating high strength wastewater with high pH variation was studied under three organic loading rates (OLRs). The reactor showed high COD removal efficiencies: 92.67, 97.44, and 98.19% corresponding to OLRs of 2.0, 3.0, and 4.8 KgCOD/m^{3}d, respectively. The first compartment showed a good buffering capacity and a distinct phase separation occurred in the ABR.**

***Keywords*—anaerobic baffled reactor, food industrial wastewater, high strength wastewater, organic loading , pH**

I. Introduction

The preservation of the environment from industrial pollution is now receiving much attention. In the food industry, the most important problem is the treatment and disposal of large quantities of wastewater, a by-product of various processing operations which contain high concentrations of soluble organic substances. These substances include sugars, organic acids, and alcohols [1]. 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 [2].

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 [3]. 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 high-rate anaerobic treatment systems have the potential to provide a renewable energy source (biogas), consume less energy and generate less sludge.

Among the new designs of anaerobic high-rate reactors, the ABR is quite promising as a new and flexible concept for application to a wide variety of domestic and industrial wastewaters including complex effluents [4]. It can be described as a series of Upflow Anaerobic Sludge Blanket (UASB) reactors, which does not require granulation for its operation [5]. As the name suggest, it is a vessel containing series of alternately hanging and standing baffles to force the wastewater to flow under and over them as it passes from the inlet to the outlet. The bacteria within the reactor tend to rise and settle with gas production in each compartment. Their movement horizontally down the reactor is relatively slow giving high biomass retention within the system. The wastewater thus gets an opportunity to come into intimate contact with a large amount of active biological mass as it passes through the ABR, while the effluent remains relatively free of biological solids [6] [7]. The constructional, biological, and operational advantages of the ABR over other systems are well documented [5]. The most significant advantage of the ABR is its ability to separate acidogenesis and methanogenesis longitudinally down the reactor, allowing the different bacterial groups to develop under most favorable conditions [8]. This separation of the two phases comes from the compartmentalized structure of the ABR. The first compartment of an ABR may act as a buffer zone to toxic material and changes in environmental parameters such as pH, temperature and organic loading in the feed, and thus allows the later compartments to be loaded with a relatively harmless, balanced and mostly acidified influent. In this respect, the latter compartments would be more likely to support active populations of the relatively sensitive methanogenic bacteria [9].

The literature survey shows that it lacks on investigating feed pH fluctuation on the performance of the ABR treating high-strength wastewater. Therefore, this study mainly focused on studying the performance of the ABR treating high-strength synthetic food industrial wastewater with high pH fluctuations under three different organic loading rates (OLR) and investigating whether that reactor with such conditions would promote phase separation.

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II. Materials and Methods

A. Lab-Scale ABR

A laboratory scale ABR was 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 downflow and upflow regions. The width of the downflow and upflow 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 45° angle to direct the flow evenly through the upcomer. The liquid flow is alternatively upwards and downwards between compartment partitions. An additional mixing was not supplied to the compartments of the reactor. Sampling ports were located in the middle of the top of each compartment allowing drawing biological sludge, and liquid samples. The produced gas was collected via porthole in the top of each compartment separately. A variable speed peristaltic pump (Masterflex L/S) was used to control feed rate from influent 10 L flask into the reactor. The effluent was collected in a plastic container. To maintain anaerobic conditions, the sampling ports of the reactor and the fittings were sealed after inoculation. The reactor was maintained at 35° C using a 50 watts aquarium heater in each compartment.

B. Feed and Seed Sludge

The reactor was fed with synthetic wastewater containing glucose as a carbon source. Synthetic wastewater was used to minimize variations in wastewater composition between experiments. 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 [10]. In order to prevent the build-up of a localized acid zone in the reactor, sodium bicarbonate was used for supplementing the alkalinity.

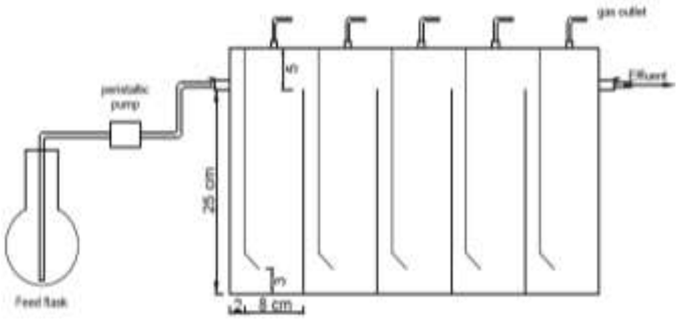

Figure 1. Schematic diagram of lab-scale anaerobic baffled reactor.

The reactor was 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 volatile suspended solids (VSS) values used in other studies undertaken on ABRs [5].

C. Analytical Methods

Supernatant liquor, gas and sludge samples were taken separately from the effluent and each compartment, beginning with the last compartment and moving towards the first, to prevent air intrusion and to maintain anaerobic conditions. Oxidation-Reduction potential (ORP) and pH values were measured daily with a calibrated pH-meter (Digital pH/ mV/ ORP meter kit). Alkalinity, volatile fatty acids (VFA), and sludge height were measured daily while COD and suspended solids (SS) were determined every other day. VSS was measured on a regular basis after attaining steady-state at all the OLRs. All the parameters were determined according to Standard Methods for the Examination of Water and Wastewater [11], except VFA and Alk. VFA and Alk were determined as per the procedure suggested by [12]. Solids retention time (SRT, θ_c), food-to-microorganism ratio (F/M), and methane production rates were calculated according to [13].

D. Operation Conditions

After inoculation, the reactor was allowed to stabilize for 24 h without further modification before starting the experiments. The HRT was kept constant at 3 days while OLR was increased after reaching steady-state in stepwise fashion till the desired strength. Three different steady states were reached. Table I shows a summary of the reactor operation conditions. Influent pH values varied along the day every day from alkaline to acidic.

III. Results and Discussions

A. Performance of the ABR System

COD removal efficiencies for the three operating stages were introduced in Table 1. As OLR increased, COD removal efficiencies increased. This was probably the net result of increased substrate concentrations which increased the substrate flux into the bioaggregates thereby increased the growth rate of internal microbe. This led to an enhanced removal rate of intermediates to methane, the production of more gas, enhanced mixing [14]. However, increasing the initial OLR enhanced the biological oxidation up to a certain point at which OLR started to inhibit the degradation rate [15].

The average characteristics of the ABR system after reaching steady-state for the 2nd and 3rd stages are summarized in Table II. Although COD removal efficiencies of the five

TABLE I. THE OPERATION PARAMETERS FOR ABR OPERATION

Stage	HRT (d)	Influent pH ranges	Influent COD (g/l)	OLR (Kg COD/m3 d)	Duration (d)	COD removal (%)
1st	3	7.51 – 4.46	6.0	2.0	5	92.67
transition	3	7.60 – 5.00	6.0 – 9.0	2.0 – 3.0	13	-
2nd	3	7.80 – 4.65	9.0	3.0	8	97.44
transition	3	8.00 – 4.14	9.0 – 14.4	3.0 – 4.8	18	-
3rd	3	8.26 – 4.43	14.4	4.8	9	98.19

compartments of the ABR at the 3rd stage were less than those obtained from the 2nd stage except for the second compartment, the overall COD removal efficiency at the 3rd stage was higher. VSS/SS ratios decreased along ABR compartments till the third compartment then increased towards the later ones due to the complete acclimation of methanogens at steady-state. VSS/SS ratios at the 3rd stage were less than those at the 2nd stage in all compartments except the first one. The results also revealed that high F/M ratios (> 0.75) encouraged COD removal in the first and second compartments while lower ratios were preferred in later ones. SRT and methane production rate values at the 3rd stage were higher than the values at the 2nd stage.

B. *pH and ORP*

Fig. 2 introduced pH values in each compartment of the ABR during the operation time. For the most part, pH increased along the five compartments of the ABR as the acids and alcohols generated in the first compartments were consumed until the end of treatment, which indicates possible phase separation ability for ABR. Apparently; there were gradually decreases in the first compartment pH while slight decreases in second compartment pH were observed. 6.0 g$NaHCO_3$ were put daily into the first compartment to prevent reactor souring. Although pH profiles showed fluctuations along the stage operation time, the fluctuation in compartment 3 was smaller compared with compartments 1 and 2. pH values of that compartment did not decrease below 6.5 which encouraged methanogenic bacterial growth. pH values of compartments 4 and 5 were almost constant and the same along the various OLRs during operation time. pH results from the last three compartments showed reactor great stability and buffering capacity under variations of influent pH values.

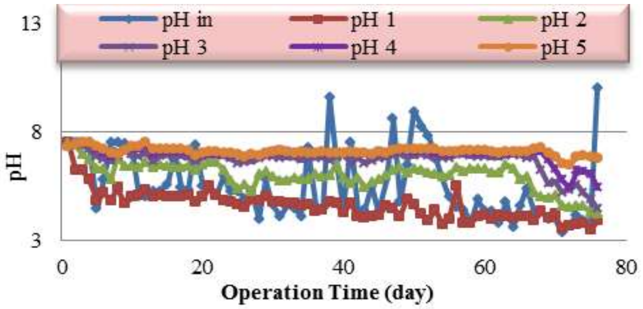

Figure 2. pH variation along the ABR compartments

Fig. 3 shows ORP values in all compartments during the operation time of the third stage. The values dropped down along the ABR compartments from –192mV in the first compartment to –412mV in the fifth one at steady-state which emphasized the phase separation acting of the reactor. At ORP values less than –100mV, the degradation of organic compounds proceeds as one portion of the compound is reduced while another portion of the compound is oxidized. This form of anaerobic degradation of organic compounds is commonly known as mixed-acid fermentation because a mixture of acids, for example, acetate, butyrate, formate, and propionate, are produced. A mixture of alcohols is also produced during fermentation. At ORP values less than –300mV, anaerobic degradation of organic compounds and methane production occur. During methane production, simple organic compounds such as acetate are converted to methane, and carbon dioxide and hydrogen are combined to form methane [16]. [17] reported that the methanogens require an extremely reducing environment, with redox potentials as low as -400 mV which is in agreement with the results. It could be found that ORP was inversely related with pH in most cases.

C. *Bicarbonate Alkalinity and TVFA*

Fig. 4 illustrates the variation of bicarbonate alkalinity (Bic.Alk) and total VFA concentrations along the ABR compartments with time. Generally, it was found that the acidogensis is the major step of the anaerobic treatment in the first compartment at OLR of 4.8 KgCOD/m^{3}d and in the first and second compartments at lower OLRs. The third to fifth compartments are the major removal steps for methanogensis where the TVFA/Bic.Alk ratios were less than 0.4. Therefore, the TVFA concentrations were high in the first compartments and decreased towards the last compartments. [18] reported that values of TVFA/Bic.Alk below 0.4 indicated reactor stability. Also HCO_3 alkalinity values between 1250 and 2500 mg/L indicated the buffering capacity of the ABR for methanogensis [19].

D. *Performance of the First Compartment of the ABR*

Fig. 5 shows the variations of COD removal efficiencies in the first compartment regarding the organic loading rates. At normal operation, the removal efficiencies ranged between 30 – 50%. It was noticed that the variations of the first compartment removal efficiencies did not affect the overall removal efficiency, which probably referred to the great stability of the ABR reactor. In the 5th and 13th days of operation, COD removal efficiency reached 82.67 and 51.4 %, respectively. A possible explanation is that the special pH adjustments before the feeding by adding NaOH in the influent flask might have favored the methanogenic activity in the first compartment at the first hours of the feeding time (24 hrs.). Whereas at the last hours influent pH values dropped, consequently the pH in the first compartment was low and its COD removal dropped, indicating a predominance of acidogenesis over methanogenesis. It was also noticed that the first compartment of the reactor could tolerate the fluctuation of the feed pH and act as a buffer zone resisting pH variations

TABLE II. AVERAGE CHARACTERISTICS OF THE ABR SYSTEM ON STEADY-STATE

Parameter		2nd Stage (OLR= 3.0 $KgCOD/m^3d$)						3rd Stage (OLR= 4.8 $KgCOD/m^3d$)					
		Influent	*Compartment*					*Influent*	*Compartment*				
			1	*2*	*3*	*4*	*5*		*1*	*2*	*3*	*4*	*5*
COD (mg/l)		9000	5040	4760	1550	440	230	14400	10020	3670*	1230	430	260
COD_{rem} (%)	Individual	-	44.00	5.56	67.43	71.61	47.73	-	30.42	63.37	66.49	65.04	39.53
	overall	-	44.00	47.11	82.78	95.11	97.44	-	30.42	74.51	91.46	97.01	98.19
VSS/SS		-	0.825	0.780	0.631	0.688	0.796	-	0.851	0.598	0.522	0.569	0.642
F/M (d^{-1})		-	0.965	0.623	0.519	0.191	0.04	-	0.755	1.772	0.542	0.233	0.058
SRT (d)		-	258.069					-	3287.46				
CH_4 production rate (l/l/d)		-	1.103					-	1.778				

and protecting the subsequent compartments. VSS/SS ratios in that compartment were 0.871, 0.825, and 0.850 corresponding to OLRs of 2.0, 3.0, and 4.8 KgCOD/m3d, respectively. High content of microorganisms in first compartment sludge formed a stable micro-ecological system that could preserve the stability of the system against shock loads through internal adjustment[14].

E. *Solids Profile and Microbial Community*

Fig. 6 shows great SS variations in each compartment of the ABR. Also, it shows decreases in the SS concentrations with time except in compartment 3 and 4. It should be noted that these values were calculated depending on sludge bed heights which were measured from only one side of the reactor.

It was clear from visual observation of the lab-scale ABR that after about a month of operation, a significant change in the nature of sludge bed was observed, especially in the first compartment. ABR was initially started with flocculent sludge of dark color. Soon after startup, white-grey sticky mass started to form in the downflow region of the first compartment and spread slightly downstream. That was consistent with [20] which reported that the biomass was found to be bacteria of the *Enterobacteriaceae* genus that can use glucose as a sole carbon source. The physical appearance of the sludge gradually changed with the formation of small granules with time.

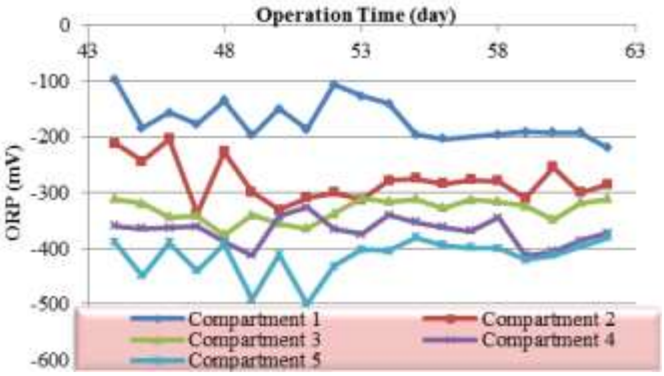

Figure 3. variation of ORP in ABR compartments

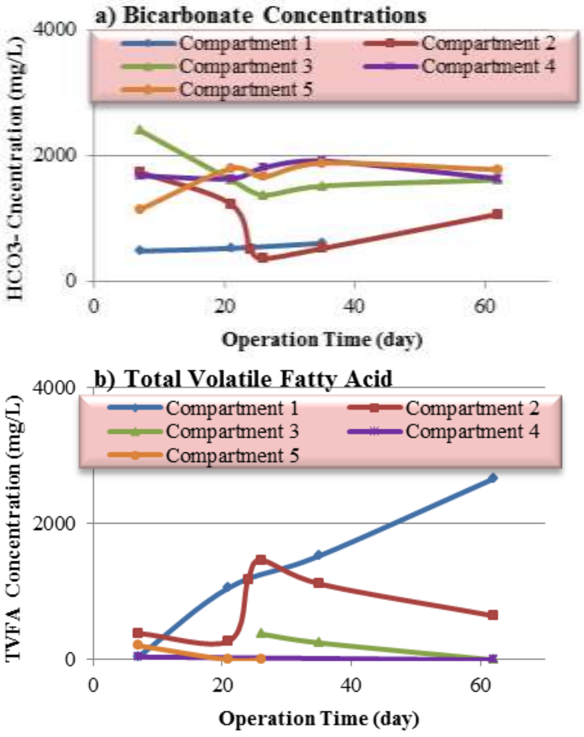

Figure 4. Changes in Bic.Alk and TVFA in ABR compartments

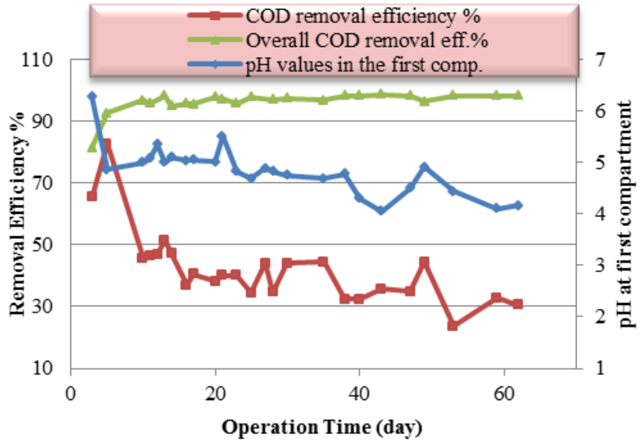

Figure 5. correlation between pH and COD removal in the 1st compartment and the entire

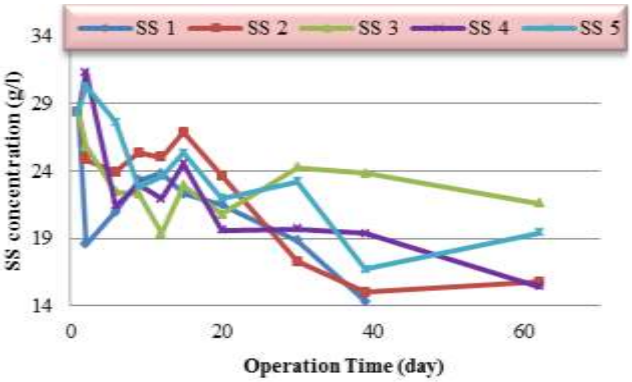

Figure 6. Suspended solids profile along the ABR compartments

IV. Conclusion

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

- Anaerobic Baffled Reactor showed high COD removal efficiencies (92.67 – 98.19%).
- ABR showed a good buffering capacity despite the great changes in influent pH.
- pH measurements within compartments show that significant acidification occurred in the first compartments. Consequently, there was an obvious phase separation in the reactor which emphasized the reactor performance.
- ORP results also demonstrated the reactor phase separation.
- From solids results, it can be concluded that the growth rate of fermentative bacteria is faster than that of acetogenic and methanogenic bacteria.

In brief, these results illustrate the potential of using ABR in treating food industrial wastewaters with high strength that vary in concentration. The compartmentalization of the ABR provides a degree of phase separation such that hydrolysis and acidogensis of organic material in the early compartments can proceed at pH values that are lower than the optimal range for methanogenesis which dominant in the later compartments where pH values remain near neutral.

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