# Effect of Influent Concentration and Hydraulic Retention Time on the Performance of an Anaerobic Hybrid Reactor Treating Wastewater from Washing of Sugarcane Bagasse

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## ABSTRACT

In the pulp and paper industry, several hundred thousand tonnes of sugarcane bagasse may be received from a sugar mill annually during December and May and is stored using a wet storage method in the bagasse yard for use as raw material throughout the year. This method of storing bagasse generates approximately 7,000 $m^3$ of wastewater. Anaerobic treatment is an effective means of biodegradation of organic matter in wastewater and biogas that can be used to produce an alternative fuel. This work investigated the effects of the influent concentration and hydraulic retention time (HRT) on the treatment of bagasse wash wastewater. An anaerobic hybrid reactor (AHR) was chosen and the chemical oxygen demand (COD) removal efficiency and biogas yield were determined to evaluate the optimum operating parameters. Two laboratory scale AHRs (A1 and A2) were operated at a constant HRT of 2 d (A1) and 4 d (A2) and they were fed with influent concentrations of 5 to 20 g $COD.L^{-1}$. The results showed that the COD removal efficiencies of A1 and A2 were in the range 76–93% and 91–98%, respectively. The biogas yield of A2 was higher than that of A1 throughout the course of the experiment. The biogas yields of A1 ($Y_{A1}$) and A2 ($Y_{A2}$) were 0.498 and 0.540 $L.g^{-1}$ $COD_{added}$, at an influent concentration of 20 g $COD.L^{-1}$; they increased linearly with the concentration in the wastewater influent and it was found that $Y_{A1} = 0.0509$ (influent COD) $+ 0.1683$ equation with the coefficient of determination ($r^2$) = 0.9223 and $Y_{A2} = 0.0390$ (influent COD) $+ 0.2791$ with $r^2 = 0.8921$. The methane content of the biogas from both reactors was as high as 70%.

**Keywords:** anaerobic hybrid reactor, influent concentration, hydraulic retention time, performance

## INTRODUCTION

In the pulp and paper industry, several hundred thousand tonnes of sugarcane bagasse is received from a sugar mill annually and is used as raw material and is stored in bagasse yards using the wet storage method for about a year (Thongbai Phainarin, production department manager of a

pulp and paper mill, personal communication, September 22, 2009) . During storage, the material is kept wet by sprinkling water over the pile of bagasse to prevent bagasse conflagration and to preserve the bagasse quality and about 7,000 $m^3$ of wastewater is accumulated in a stacker (Thongbai Phainarin, production department manager of a pulp and paper mill, personal communication,

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September 22, 2009). This wastewater has relatively high chemical oxygen demand (COD) compared with wastewater during bleaching and machining of the paper (Chinnaraj and Roa, 2006) and it is essential to treat it to remove organic compounds.

Anaerobic treatment is regarded as one of the most interesting alternative technologies for treating wastewater and for methane production as it has been shown to be a very cost-effective alternative to aerobic processes with savings in energy and supplying nutrients (Ho and Sung, 2010). Anaerobic digestion involves a multi-stage degradation of organic compounds by the action of a consortium of microorganisms via a variety of intermediates and methane is the ultimate product (Fang *et al.*, 2011). Anaerobic treatment processes are classified as being either attached growth processes or suspended growth processes; however, the application of these techniques has drawbacks, such as washout of active biomass in the suspended growth process (Najafpour *et al.*, 2006) and mass transfer between substrate and biomass in the attached growth process (Chaiprasert *et al.*, 2003). However, an anaerobic hybrid reactor (AHR) utilizes a combination of attached and suspended growth systems and it is considered to successfully retain biomass (Pandian *et al.*, 2011). An AHR contains a sludge bed in its lower part and a filter in its upper part and it is a useful alternative when the granular biomass is difficult to cultivate or to maintain. AHRs have been used for the treatment of low and medium strength wastewaters, for example, tapioca starch wastewater (Chaiprasert *et al.*, 2003), sago wastewater (Banu *et al.*, 2006), distillery spent wash (Kumar *et al.*, 2007) and palm oil mill effluent (Meesap *et al.*, 2012). The operational parameters of hydraulic retention time (HRT) and influent concentration also affect the performance and stability of these systems (Kayranli and Ugurlu, 2011). Therefore, in order to apply AHR for bagasse wastewater treatment, optimization of these parameters is required.

The aim of this work was to evaluate the treatment of bagasse wash wastewater using an AHR with nylon fibers providing the supporting structure. The effects of influent concentration and HRT on the performance and the stability of the digester were investigated.

## MATERIALS AND METHODS

### Wastewater and seed sludge

The sugarcane bagasse wash wastewater was collected from the stacker of a pulp and paper industry (EPPCO, Nakhon Sawan, Thailand) between November 2012 and April 2013; it was stored at 4 °C until required. The characteristics of this wastewater, which was fed into the reactor, are presented in Table 1. The seed sludge was obtained from an anaerobic fixed-film reactor used to treat wastewater from the production of tapioca starch (Cholcharoen Co. Ltd.; Chonburi, Thailand). The granules of sludge were ground and passed through a 0.4 mm plastic sieve. The specific methanogenic activity of the inoculum was 0.2 L $CH_4$. $g^{-1}$ volatile suspended solid.$L^{-1}$.

### Equipment

A diagram of the experimental equipment is shown in Figure 1. Two identical transparent acrylic cylindrical AHRs were used. The reactors had a working volume of 5 L with an internal diameter of 9 cm and a height of 80 cm. Each reactor had its working volume split equally into a sludge bed at the bottom and a packed bed in the upper part. In the packed zone, nylon fibers (purchased locally) were used as the supporting medium. The nylon fibers were 0.1 cm in diameter and 40 cm in length. The medium was installed in the upper half of the reactors with 3 bunches of 184 pieces having a total surface area of 136 $m^2.m^{-3}$. The wastewater was fed (upwards) by a peristaltic pump. A valve on the top plate of each reactor was connected to a gas measurement apparatus and the reactors were operated at ambient temperature (approximately 28–30 °C).

**Table 1** Characteristics of sugarcane bagasse wash wastewater and operational periods at various influent concentrations.

| Influent concentration (g COD.L⁻¹) | Parameter | | | | | | | Operational period (d) | |
|---|---|---|---|---|---|---|---|---|---|
| | pH | Alkalinity (mg.L⁻¹) | TVA (mg.L⁻¹) | TS (mg.L⁻¹) | TVS (mg.L⁻¹) | TSS (mg.L⁻¹) | VSS (mg.L⁻¹) | A1 | A2 |
| 5 | 6.91 | 2,270 | 2,210 | 4,290 | 1,730 | 190 | 110 | 36–45 | 37–50 |
| 7.5 | 7.73 | 2,040 | 830 | 2,900–3,590 | 650–1,320 | 565–570 | 160–230 | 46–57 | 51–62 |
| 10 | 4.27 | 410 | 3,350 | 3,880 | 700–1,580 | 700 | 630 | 84–106 | 84–106 |
| 12.5 | 4.13 | 260 | 4,040 | 4,740 | 3,210 | 640 | 470 | 107–118 | 107–118 |
| 15 | 4.31 | 620–720 | 5,100 | 6,590 | 4,250 | 170 | 125 | 119–126 | 119–132 |
| 17.5 | 4.23 | 590–610 | 6,140 | 9,300 | 6,110 | 520 | 390 | 127–133 | 133–147 |
| 20 | 4.13 | 180–410 | 8,900 | 11,680 | 7,630 | 310 | 200 | 134–141 | 148–162 |

COD = Chemical oxygen demand; A1 = Anaerobic hybrid reactor 1; A2 = Anaerobic hybrid reactor 2.
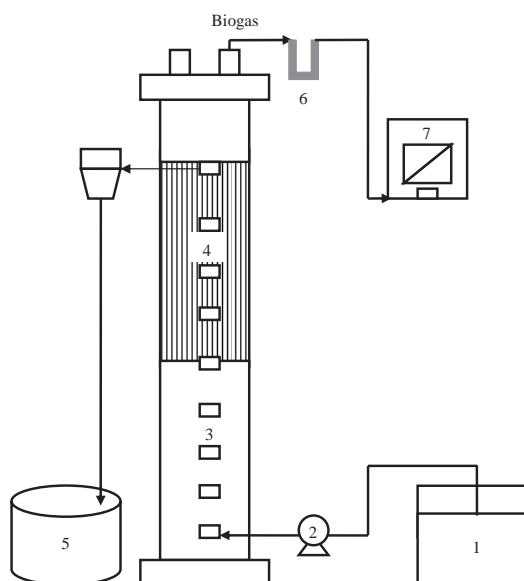


**Figure 1** Schematic diagram of an anaerobic hybrid reactor: (1) Feed tank; (2) Peristaltic pump; (3) Suspended zone; (4) Attached zone; (5) Effluent tank; (6) U-tube; (7) Gas measurement apparatus.

**Experimental procedure and analytical methods**

The reactors were started up with an inoculum concentration of 5 g.L⁻¹. The influent concentration was increased stepwise from 5 to 20 g COD.L⁻¹ without any pH and alkalinity adjustments. The reactors were operated at each influent concentration until the process performance reached a steady state and they were kept running continually for three cycles of HRT. The operational periods of both reactors under each set of conditions are presented in Table 1. The HRTs of both reactors (A1 and A2) were kept constant for 2 and 4 d, respectively. Effluent was examined to evaluate the performance and the stability of the reactors. The pH, alkalinity and total volatile acids (TVA) were determined according to standard methods (American Public Health Association, 1995). The composition of biogas was determined using gas chromatography (Class-GC 14B; Shimadzu Corp.; Tokyo, Japan) fitted with a Porapak-N column and a thermal conductivity detector. The oven, injector and detector temperatures were 70, 120 and 120 ºC, respectively. Helium was used as the carrier gas at a flow rate of 30 mL.min⁻¹. The monitored parameters were measured on 5 d in each week throughout the study. At each steady-state condition, (defined by steady biogas production within ±15% deviation), the COD and specific methanogenic activity (SMA) were measured. The total COD and soluble COD were determined in triplicate according to standard methods (American Public Health Association, 1995). The SMA test was carried out using 120 mL serum vials with 100 mL of total volume and acetate as the substrate. Determination of SMA was according to the method of Isa *et al.* (1993).

## RESULTS AND DISCUSSION

### Effect of influent concentration on the performance of anaerobic hybrid reactors

The efficiency of removal of total COD observed at different influent concentrations is illustrated in Figure 2. The results indicated that efficiency was affected by increasing influent concentrations in A1. The COD removal efficiency decreased from 90% to 76% and 79% when 7.5 and 10 g COD.L$^{-1}$ influent concentrations, respectively, were fed to reactor A1 and these decreases were attributed to an insufficient time to generate biomass and reach a steady-state condition. Once steady-state was reached, the total COD (TCOD) removal efficiency increased to 91–93%. In contrast to A1, the TCOD reductions were 91%–98% at all influent concentrations in A2. The bagasse wastewater contained easily biodegradable components as shown by almost complete removal of TCOD. It is possible that the mass transfer rate was enhanced with a higher substrate concentration under steady-state conditions. Therefore, the COD removal efficiency increased with increasing COD concentration of the influent (Sun *et al*., 2012).
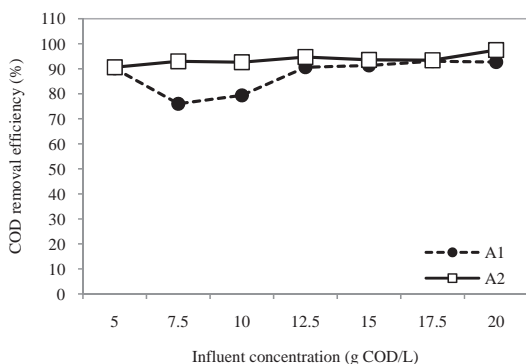


**Figure 2**  Total chemical oxygen demand (COD) removal efficiency of two anaerobic hybrid reactors (A1 and A2) at different influent concentrations for constant hydraulic retention times of 2 d (A1) and 4 d (A2).

Figure 3 shows the variation of the pH and the TVA to alkalinity ratio with influent concentration. The pH varied between 7.5 and 8.1 in both reactors and remained within the optimal pH range for a methanogenic process (Raposo *et al*., 2004). In relation to the alkalinity values, it was observed that the buffering capacity of the reactors was maintained at favorable levels. The results indicated that alkalinity in the range of 1,630–2,810 mg.L$^{-1}$ as CaCO$_3$ was sufficient to prevent a decrease in the pH (Table 2). The TVA:alkalinity ratio has been used as a measure of process stability (Rincon *et al.,* 2008), with a ratio of less than 0.4 mg acetate per mg CaCO$_3$ indicating that the system is stable and ratios greater than 0.8 indicating inhibition of methanogens resulting in process failure. When the influent concentration was increased from 5 to 7.5 g COD.L$^{-1}$, there was a corresponding decrease in the stability of the reactors because of an increase in the TVA:alkalinity ratio to a value of 0.51–0.68. An increase in the TVA concentration in the influent and a short HRT led to the accumulation of TVA in the reactor. Nevertheless, the systems recovered quickly and adapted to the new conditions thereafter. Then, the TVA: alkalinity ratio decreased to 0.3–0.4 because the accumulation of TVA in the reactors declined. However, the TVA concentration of the effluent in A1 was higher than that of A2 (Table 2) presumably because of the shorter contact time between the influent wastewater and the microorganisms in the system.

The biogas yield tended to increase linearly with increasing influent concentration in both reactors (Figure 4). The biogas yield of A2 was higher than that of A1 throughout the experiment. When the influent concentration was increased from 5 to 12.5 g COD.L$^{-1}$, the biogas yield of A1 ($Y_{A1}$) increased more than that of A2 ($Y_{A2}$). This can be described by linear equations where $Y_{A1} = 0.070$ (influent COD) + 0.129 with a regression coefficient ($r^2$) = 0.934 and $Y_{A2} = 0.060$ (influent COD) + 0.226, $r^2 = 0.954$. However,
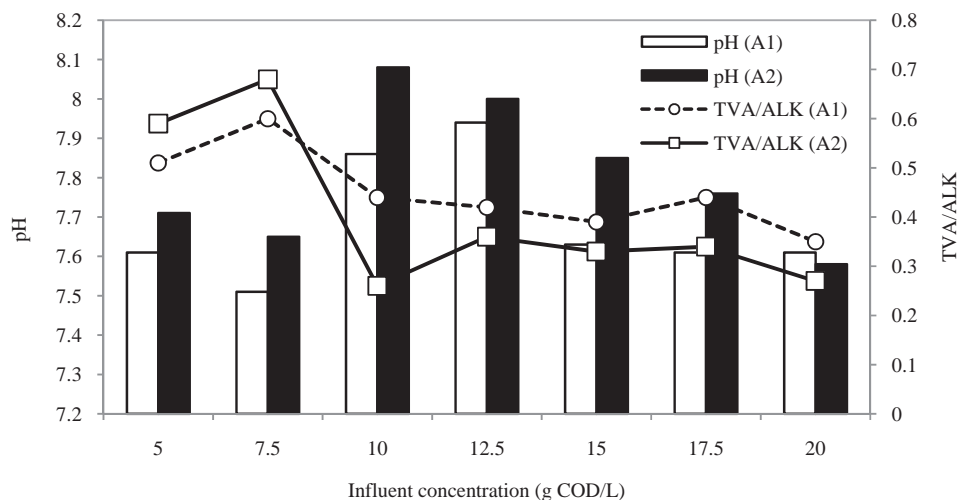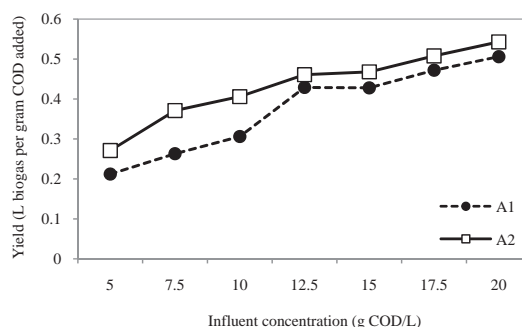
**Figure 3** pH and total volatile acids:alkalinity ratio (TVA/ALK) at different influent concentrations of two anaerobic hybrid reactors (A1 and A2) for constant hydraulic retention times of 2 d (A1) and 4 d (A2). (COD = Chemical oxygen demand.)

when the influent concentration was increased from 12.5 to 20 g COD.L$^{-1}$, the increase in the biogas yield of A1 was similar to that with A2 and could be expressed by $Y_{A1} = 0.027$ (influent COD) $+ 0.39$, $r^2 = 0.892$ and $Y_{A2} = 0.028$ (influent COD) $+ 0.423$, $r^2 = 0.938$. The maximum biogas yields of A1 and A2 were 0.498 and 0.540 L.g$^{-1}$ COD$_{added}$, respectively, at an influent concentration of 20 g COD.L$^{-1}$. The methane yield coefficient is defined as the ratio of methane produced to the COD utilized. Maximum methane yields of 0.430 and 0.446 L CH$_4$. g$^{-1}$COD$_{removed}$ were observed in A1 and A2, respectively, and the methane content in the biogas of both reactors was approximately 70% at steady state. The methane yield observed in this study was much higher than those noted in other wastewater studies that contained carbohydrates (Chaiprasert *et al*., 2003, Banu *et al*., 2006, Kumar *et al*., 2007). This finding reveals the high efficiency of energy recovery obtained by the anaerobic treatment of sugarcane bagasse wash wastewater.

The microbial quality of the sludge zone was estimated using the specific methanogenic activity (SMA) test at the steady state of each condition (Table 2). The SMA values of both reactors gradually increased when the influent concentration was increased from 5 to 12.5 g COD.L$^{-1}$ and the SMA value of A2 was higher than that of A1. Subsequently, when the influent concentration was increased, the SMA of the sludge zone decreased while the methane yield increased (Table 2), and it is suggested that the increase in the methane yield might have been due to the increased activity of methanogens in the packed zone. It is possible that the microbial biomass, especially the methanogens, had migrated from the sludge zone to become attached more extensively to the supporting medium.



**Figure 4** Biogas yield at different influent concentrations of two anaerobic hybrid reactors (A1 and A2) for constant hydraulic retention times of 2 d (A1) and 4 d (A2). (COD = Chemical oxygen demand.)

**Effect of hydraulic retention time on the performance of anaerobic hybrid reactors**

       The hydraulic retention time (HRT) is one of the most important operating parameters influencing the economics of digestion systems (Kim *et al*., 2008) . The results indicated that the HRT affected the performance of the reactor (Table 3) because the operation of a reactor with a long HRT resulted in a longer contact time between the substrate and biomass. At an organic loading rate (OLR) of 5 g COD.L$^{-1}$ .d$^{-1}$, the A1 and A2

**CONCLUSION**

       The results revealed the promising potential of the anaerobic treatment of sugarcane bagasse wash wastewater. Using AHRs, a high value of COD removal at an OLR of 10 g COD.L$^{-1}$.d$^{-1}$ was achieved. In addition, extensive biogas production and good biogas quality were observed, indicating that the system operates economically and has efficient energy recovery.

**Table 2** Performance of anaerobic hybrid reactor at various influent concentrations and hydraulic retention times.

| COD$_{in}$ (gL$^{-1}$) | Alkalinity (mg CaCO$_3$.L$^{-1}$) | | TVA (mg acetate.L$^{-1}$) | | Methane content (%) | | Methane yield (L CH$_4$.g$^{-1}$ COD$_{removed}$) | | Specific methanogenic activity (g COD-CH$_4$.g$^{1-}$VSS.d$^{-1}$) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | A1 | A2 | A1 | A2 | A1 | A2 | A1 | A2 | A1 | A2 |
| 5 | 2250 | 1870 | 1150 | 1120 | 82.85 | 80.19 | 0.207 | 0.230 | 0.033 | 0.148 |
| 7.5 | 2170 | 2070 | 1290 | 1420 | 52.06 | 57.63 | 0.211 | 0.226 | 0.144 | 0.182 |
| 10 | 1630 | 2120 | 1240 | 430 | 68.09 | 69.31 | 0.274 | 0.305 | 0.165 | 0.202 |
| 12.5 | 1770 | 1830 | 720 | 680 | 71.14 | 68.7 | 0.320 | 0.352 | 0.201 | 0.204 |
| 15 | 2370 | 2150 | 970 | 710 | 69.78 | 70.64 | 0.319 | 0.389 | 0.172 | 0.132 |
| 17.5 | 2890 | 2170 | 1440 | 750 | 73.58 | 69.93 | 0.380 | 0.423 | 0.112 | 0.184 |
| 20 | 2580 | 2810 | 890 | 760 | 72.03 | 72.69 | 0.430 | 0.446 | 0.140 | 0.131 |

COD$_{in}$ = Influent chemical oxygen demand; TVA = Total volatile acids; COD$_{removed}$ = Removed chemical oxygen demand; VSS = Volatile suspended solid; A1 = Anaerobic hybrid reactor 1; A2 = Anaerobic hybrid reactor 2.

reactors were fed with the influent concentration of 10 and 20 g COD.L$^{-1}$, respectively. A2 was operated for a longer HRT and achieved a higher process efficiency than A1 as shown by its higher COD removal, biogas yield and methane yield. The biogas and methane yield of A2 were 1.7 times higher than those of A1.

       As the AHR accounted for more than 90% of the COD at an HRT of 2 d, it is intended to determine the optimum HRT in future work in order to be able to reduce the reactor volume and the cost of investment. Since the COD of sugarcane bagasse wash wastewater varies upon storage, the variation of operating conditions

**Table 3** Performance of the reactors at organic loading rate of 5 g COD.L$^{-1}$.d$^{-1}$ under different hydraulic retention time (HRT)s.

| Reactor | HRT (d) | COD removal efficiency (%) | Biogas yield (L.g$^{-1}$ COD$_{added}$) | Methane yield (L CH$_4$.g$^{-1}$ COD$_{removed}$) |
|---|---|---|---|---|
| A1 | 2 | 79 | 0.304 | 0.274 |
| A2 | 4 | 98 | 0.540 | 0.446 |

COD = Chemical oxygen demand; COD$_{added}$ = Added chemical oxygen demand; COD$_{removed}$ = Removed chemical oxygen demand; A1 = Anaerobic hybrid reactor 1; A2 = Anaerobic hybrid reactor 2.

(OLR and HRT) may be associated with changes in the number of microbes within the reactor. To understand the relationships that link operating parameters, reactor performance and the ratio of methanogens to non-methanogens in the reactors, further investigation will be initiated in the near future. The relative proportions of methanogens and non-methanogens generated under different operating conditions will be examined.

## ACKNOWLEDGEMENTS

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