High rate biological contactor system using waste activated sludge from trickling filter/solids contact process

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ABSTRACT

A high-rate biological contactor process (HRBC) can be used as primary treatment instead of a clarifier to remove particulate, colloidal and soluble fractions of organic matter via biosorption plus flotation and divert it to anaerobic digestion for methane production, simultaneously reducing secondary aeration energy demand. Pilot and bench tests were conducted at a range of contact times (15–60 min) and contactor dissolved oxygen (DO) (0.2–2.0 mg/L) using waste activated sludge (WAS) from a trickling filter/solids contact (TF/SC) process in the HRBC. Biosorption performance was lowest when contact times were <30 min and unstable at DO < 0.5 mg/L. The overall average of 20% sCOD capture was similar to previous findings by others using WAS from conventional AS. The biomethane potential (BMP) of the HRBC float material can be as high as that of primary sludge (340–400 mL CH₄/g VS), which is much greater than WAS. Operating the HRBC with a long contact time (>30 min) or with high DO (>1 mg/L) increases the amount of biosorption but reduces the BMP of the float. It was also found that biosorption only effectively occurs when a WAS is paired with the wastewater from the same facility.

Key words | biomethane potential (BMP), biosorption, high-rate biological contactor (HRBC), trickling filter/solids contact (TF/SC), waste activated sludge (WAS)

HIGHLIGHTS

- HRBC followed by dissolved air flotation is a new primary treatment that can remove particulate, colloidal and soluble fractions of organic matter.
- WAS from the secondary treatment process is in contact with the wastewater in the contact tank to promote biosorption.
- Other pilot tests and the only full-scale plant are all using the WAS generated by the suspended activated sludge processes.
- This research showed that WAS from biofilm secondary process can also be used as the biosorbent in the HRBC process.
- In addition, the biomethane potential of the float material, which consisted of the particular organic matter, suspended solids and the WAS with the adsorbed/absorbed organic matter, can be as high as the primary sludge.
INTRODUCTION

Typically, municipal wastewater treatment plants (WWTPs) are large utility power consumers. To reduce energy demands, many smaller municipal WWTP managers invest their resources to implement energy conservation technologies. These known technologies include using premium efficiency motors, adding adjustable frequency drives (AFDs) to pumps and blowers, converting coarse bubble diffusers to fine or ultra-fine bubble diffusers, and using higher efficiency blowers for aeration. Large municipal WWTPs tend to have the luxury to go a step further by investing in energy recovery to further reduce the use of utility power. For a large municipal WWTP, a common strategy to achieve energy recovery is to utilize methane gas, a product of the anaerobic digestion process, to generate electricity to supply in-plant power needs. The greater the methane gas production in the anaerobic digestion process, the more electricity that can be generated by the plant to offset utility-supplied electricity. Diverting more organics from the influent wastewater stream to the biosolids stream, prior to the secondary aeration basins, can increase methane gas production in the anaerobic digesters. Other benefits of such an approach include reducing the organic load and therefore the aeration energy required to treat the wastewater.

A high-rate biological contactor (HRBC) followed by dissolved air flotation (DAF) as a liquid-solid separation process is considered a new primary treatment process that promotes carbon diversion. Evoqua, an equipment manufacturer, currently holds a patent on a version of this process known as ‘Captivator’. The HRBC is a small aerated tank with typically less than an hour HRT. The waste activated sludge (WAS) from the secondary treatment process is mixed with the screened and de-gritted wastewater in this contactor. In the HRBC system, the solids retention time (SRT) for the HRBC system is the same as the HRT. In the HRBC process, the microorganisms in the WAS not only coagulate the colloidal fraction of the organic compounds, but also absorb the soluble biodegradable fraction of the organic matter. Due to the short HRT in the system, it is believed that the microorganisms do not oxidize the soluble biodegradable organic matter. In this paper, this phenomenon is defined as biosorption. The WAS plus biosorbed organics are separated by the DAF and sent to anaerobic digestion for methane production. The concept of biosorption using activated sludge to remove organic matters in raw wastewater was first introduced and tested by Ullrich and Smith (Ullrich & Smith 1951). There are many definitions of biosorption. According to Jorand et al. (1995), biosorption describes adsorption and absorption into the cells, with storage as glycogen, and without biodegradation of the organic matter. Guellil et al. (2001) indicated that biosorption describes the transport of organic matter in the wastewater to the activated sludge by retention within the flocs due to physico-chemical reactions caused by electrostatic or hydrophobic interactions. For Gadd (2009), biosorption is a physico-chemical process and includes mechanisms such as absorption, adsorption, ion exchange, surface complexation, and precipitation.

To date, the only full-scale plant and all the pilot tests conducted on this HRBC process used WAS generated from activated sludge processes. The Agua Nueva Water Reclamation Facility (ANWRF) in Tucson, Arizona, is the full-scale plant, which uses a process similar to the HRBC system. The secondary process at this plant is a step-feed 5-stage Bardenpho activated sludge system. At ANWRF, a small aerated tank is used for flocculation/biosorption and also serves as an aerated grit chamber (AGC) (Johnson et al. 2014). The process after startup is able to achieve 65% removal efficiency of total suspended solids (TSS) and between 25 and 30% removal efficiency of soluble biochemical oxygen demand (sBOD) (Doyle et al. 2018). According to Ding et al. (2015), the average biogas production rate for the pilot HRBC system in Singapore was 15.0 m³/d, whereas it was 8.3 m³/d for the conventional AS process. However, field or pilot test data is not available when WAS from a biofilm secondary treatment process such as trickling filter/solids contact (TF/SC) process is used in the HRBC system. In this study, the impact of HRT, DO, and TSS on the performance of the HRBC system using TF/SC WAS, the bio-methane potential (BMP) of the DAF thickened float and primary sludge, and the biosorption performance using WAS from various secondary treatment processes were evaluated.

MATERIALS AND TESTING

For this study, the total chemical oxygen demand (COD) is defined as the sum of particulate COD (pCOD) and soluble (filtered) COD (sCOD). Also, sCOD consists of colloidal COD (cCOD) and the truly soluble COD that is filtered and flocculated (ffCOD). COD, sCOD, and ffCOD were
analyzed using Hach Method 8,000, TSS used Standard Methods (SM) \cite{APHA} 2540D, volatile suspended solids (VSS) used SM2540E, and BMP used an analytical method developed by Angelidaki et al. \cite{Angelidaki} using the Automatic Methane Potential Test System (AMPTS) II instrument (Sweden). Prior to measuring sCOD, the sample was filtered through a glass fiber filter paper with pore size of 1.2 μm. For measuring ffCOD, the sample prepared for sCOD measurement was flocculated by using zinc sulfate, the pH of the sample was raised to 10.5 with sodium hydroxide solution, and then it was filtered through a 0.45 μm membrane filter \cite{Mamais}. To measure the sCOD and ffCOD of the WAS, the WAS was centrifuged at 5,400 RPM (3,260 G) for 5 minutes and then the supernatant was decanted.

**Pilot test**

A Captivator pilot unit rated for 1,136 m³/d (300,000 gal/d) from Evoqua was used to examine the impact of HRT, DO and TSS on the HRBC system using TF/SC WAS and the BMP of the DAF thickened float material. The unit consists of three major components: a contactor tank with a vertical loop reactor (VLR) system for aeration/mixing, a DAF tank with pressurization system, and a control system. The VLR system uses a surface disc-type aerator to provide mixing energy and aeration. A schematic of the HRBC-DAF system is shown in Figure 1. The contact tank has an effective volume of 33.31 m³ (8,800 gal) with an HRT of 40 minutes for the rated flow. The DAF has an effective surface area of 5.95 m² (64 ft²) with a design surface overflow rate of 191.1 m³/m²/d (4,690 gal/ft²/d). The operating pressure of the pressurization system is 275–345 kPa (40–50 psi) with the air compressor sized for 5.78 m³/hr (3.4 scfm) at 689.5 kPa (100 psi). It is designed to deliver 0.01 kg/min (0.02 lb/min) of dissolved air and thus provide an air-to-solids ratio (A/S) ratio of 0.01–0.03 kg/kg. The WAS pump has a pumping capacity of 327 m³/d (60 gal/min). The wastewater sampling locations and types are presented in Table 1. The HRT had been divided into three categories: short, average and long HRT. The short HRT was defined as 15–20 minutes, average HRT was 38 minutes, and long HRT was 44–60 minutes. The pilot unit was operated under short, average and long HRT for 7, 17 and 7 days, respectively. The TF/SC treatment plant has an average influent flow of 1.14 m³/s (26 MGD), influent TSS of 322 mg/L, influent sCOD of 152 mg/L, influent total dissolved solids (TDS) of 640 mg/L, pH of 7.4, WAS TSS of 3,340 mg/L, and SRT of 1 day.

**Bench-scale biosorption test**

The bench-scale biosorption test procedure was used to simulate the HRBC process. The WAS and raw wastewater were collected from the WWTP just prior to testing (not stored/chilled). A 5-litre Plexiglass reactor (length 21 cm,
(width 13 cm, height 25 cm) was used to represent the aerated contactor in the laboratory. A magnetic stir bar was placed in the contactor, which was placed on a stir plate. A pre-determined volume of raw wastewater was added to the contactor. The mixing in the contactor was observed to ensure the wastewater was reasonably well mixed. Then a calibrated DO probe was inserted to measure the DO continuously. Air flow to a single 2-cm spherical aeration stone was then initiated and adjusted until the desired DO was stable in the reactor. This required approximately 1 minute and the air flow was approximately 10 mL/min, which is a volumetric rate of 2 m$^3$/min/1,000 m$^3$ that is much lower than in a typical aeration tank (20–30 m$^3$/min/1,000 m$^3$). The pre-determined volume of WAS was then added to the contactor and the air flow was adjusted to maintain the target DO level (approximately 20 and 30 mL/min for 0.5 and 1.0 mg/L DO, respectively). After mixing for 10 seconds, the first sample was collected and this sample was designated as the sample for '0 min'. Another sample was retrieved after 30 minutes of contact time. These experiments were conducted at room temperature (22 °C).

### Bench-scale biosorption and flotation test

This bench-scale biosorption and flotation test procedure is to simulate the HRBC and DAF as a system by using TF/SC WAS. Effluent from the biosorption test as described above was used for this portion of the test. This test was to evaluate the influence of the WAS in relation to the performance of the HRBC and DAF as a system. To begin the test, 850 mL of the biosorption effluent was placed in the DAF reactor (1-Litre plastic graduated cylinder fitted with an inlet/outlet valve located at the 300 mL level). Tap water was placed in a pressurization tank and then pressurized with air to 413.69 kPa (60 psi). The tank was shaken vigorously for 2 minutes to ensure good dissolution. 150 mL of this pressurized tap water was injected into the bottom of the DAF reactor, resulting in an A/S of 0.01–0.03 kg/kg. Three minutes were allowed for flotation separation. 100 mL of the subnatant in the DAF reactor was collected for conducting various analyses.

### RESULTS AND DISCUSSION

Although the pilot test was conducted for three months, there were a few operating issues during the test period. One main issue was the clogging of the DAF recycle system due to inadequate screening. The suction inlet of the recycle pump is only 40 mm (1–1/2 inch). This eventually had led to using primary effluent for the DAF pressurized recycle system instead of recirculating the DAF effluent. A mass balance approach is used to determine

| Table 1 | Sample locations and types |
|---------|---------------------------|
| Location | Type          | Analyzed                |
| Raw wastewater | Composite | COD, sCOD, fCOD, TSS, VSS |
| Contact tank effluent | Composite | COD, sCOD, TSS, VSS |
| DAF tank effluent | Composite | COD, sCOD, fCOD, TSS, VSS |
| DAF tank float solids | Grab | TSS, VSS, BMP |
| WAS | Grab | COD, sCOD, TSS, VSS |
| Primary effluent | Composite | COD, sCOD, fCOD, TSS, VSS |
| Primary sludge | Grab | TSS, VSS, BMP |

- **Figure 2**: sCOD loadings in HRBC.
- **Figure 3**: sCOD percent removal in HRBC.
the DAF performance to account for the addition of the primary effluent.

Pilot test – HRBC sCOD removal

Figure 2 presents the sCOD loadings in the HRBC. The data show that mixing the TF/SC WAS with the influent wastewater did facilitate sCOD removal. The sCOD percent removal rates are shown in Figure 3. The average sCOD percent removal was 20% with the highest percent removal of 62%. This average sCOD removal rate is similar to the full-scale plant at the ANWRF and a pilot test conducted in Bethlehem, Pennsylvania, except that the HRT in the TF/SC pilot test was much longer. The HRT for the AGC/flocculation tanks in ANWRF was 12.5 minutes at average design flow condition and the HRT used in the pilot test in Bethlehem was only 10 minutes. When compared the
performance with another pilot test conducted in the city of Oconomowoc, Wisconsin, the average sCOD percent removal at Oconomowoc was 13.9% with a HRT of 10 minutes. The pilot test data seems to indicate that biosorption in the HRBC process is dependent on the characteristics of the biomass as the biosorption adsorbent.

**Pilot test – DO, HRT and TSS on TF/SC HRBC performance**

Wett *et al.* (2007) indicated that organic compounds in wastewater are mainly removed by biosorption within 30 minutes of HRT. Figure 4 is to examine the DO and HRT impact on sCOD removal in the HRBC using TF/SC WAS. The average sCOD percent removal rates for short, average and long HRT were 14, 21 and 25% respectively. Based on the results, operating the HRBC in short HRT using TF/SC WAS did not provide adequate time for biosorption to take place. This seems to in agreement with a study conducted by Guellil *et al.* (2001). In accordance with Guellil *et al.*, the transfer of colloidal and truly soluble fractions of the COD to the biomass reached a steady-state after 20 and 40 minutes of mixing respectively. For the average HRT scenario, the sCOD removal rates for operating at DO < 0.5 mg/L seemed undesirable or unstable. When operating at DO > 0.5 mg/L, the minimum sCOD percent removal was 14% with an average of 24%. When the HRT in the HRBC is long, the sCOD percent removal rate increased as the DO increased.

The influence of WAS TSS concentrations in the HRBC on sCOD removal was also examined. Figure 5 presents the sCOD percent removal versus the WAS TSS concentration in the HRBC. The biomass in the pilot HRBC test was in the range of 100–400 mg/L with an average of 180 mg/L. The results show a trend that the sCOD percent removal rate increased as more WAS was mixed with the wastewater in the contactor.
Pilot test – TF/SC HRBC system float BMP

The BMP is a measurement to determine the methane production potential for a given organic material in the anaerobic digestion process. In the pilot HRBC system, the thickened float material, which was average 4% solids throughout the test, consisted of raw suspended solids with adsorbed/absorbed organics and the WAS from a TF/SC secondary process. The results showed that the primary sludge (PS) had the highest average BMP (382 mL CH\(_4\)/g VS) followed by the float and then the WAS. The average BMP value for the float was 294 mL CH\(_4\)/g VS, which was based on thirty-nine samples. Based on two samples of WAS and three samples of primary sludge (PS), the average BMP for these two materials was 166 and 382 mL CH\(_4\)/g VS respectively. These results were not unexpected since it is generally known that PS is more biodegradable than the secondary sludge (Bellaton et al. 2010). To further examine the impact of the HRBC operation on the float BMP, the data set was grouped into four categories, as shown in Table 2.

The results indicate that the BMP for the float can be as high as the PS. One interesting observation is that operating in average HRT with high DO or long HRT seems to reduce the float material biogas production potential. It was suspected that the microorganisms oxidized rather than stored the organic matter under these conditions. Based on the results, the average HRT and low DO condition had the highest average BMP of 344 mL CH\(_4\)/g VS. Although this operating condition seems to promote higher BMP, it is not the most favorable operating condition in terms of sCOD removal as described previously.

Bench-scale biosorption test – impact of type of WAS on biosorption performance

The purpose of this test was to examine the impact of WAS generated by different secondary treatment processes on biosorption performance in a laboratory controlled environment without the uncertainties or difficulties associated with a pilot test. All the tests were conducted based on an HRT of 50 minutes. Three types of WAS were used in this test: TF/SC WAS with SRT of 1 day, selector activated sludge (SAS) modified Ludzack-Ettinger (mLE) WAS with aerobic SRT of 8 days, and anoxic SAS (ASAS) WAS with aerobic SRT of 5.5 days. All three plants are municipal WWTPs. The current average daily flows are 1.14, 0.02 and 0.18 m\(^3\)/s (26, 0.5 and 4 mgd) for TF/SC, SAS mLE and ASAS plants, respectively. The raw wastewater and WAS characteristics for these three plants are presented in Table 3. For the SAS mLE plant, the WAS ffCOD was always higher than the sCOD in all analyses. The average WAS sCOD was 46 mg/L whereas the average ffCOD was 59 mg/L. This could be due to an interference such as bromide or chloride, but is undetermined. However, since only 5 or 10% by volume of WAS is used during biosorption, the impact on the results was insignificant. Therefore, no adjustment was made to the sCOD and ffCOD when calculating the sCOD and ffCOD removal.

Attempts were made to use different secondary treatment WAS with the same wastewater from one plant to examine the biosorption performance. An interesting observation was that the biosorption phenomenon only occurred when using the native pairings of WAS and wastewater.
Therefore, it was not possible to determine whether one type/age of WAS would provide better biosorption capability than another type on the same wastewater. This could be investigated at a plant that has two independent treatment trains operated at different SRTs.

To compare the biosorption performance of various secondary WAS types, a normalized sCOD and ffCOD removal per weight of WAS TSS using its own wastewater were examined as shown in Figures 6 and 7. The results show that the SAS mLE WAS had the highest, whereas the ASAS WAS had the lowest sCOD and ffCOD removal per weight of WAS TSS. The average WAS sCOD removal for ASAS, TF/SC and SAS mLE were 103.6, 173.8 and 317.6 mg sCOD/g TSS, respectively. The average WAS ffCOD removal for ASAS, TF/SC and SAS mLE were 67.7, 92.2 and 199.2 mg ffCOD/g TSS respectively. These results indicate that the effects of SRT are not obvious. While the biosorption removals are much greater for the 8-day SRT sludge than the 5.5-d SRT, the removals by the 1-d SRT sludge are greater than the 5.5-d SRT sludge. This could be due to characteristics of the TF/SC sludge, which includes humus from the TF that likely has a long effective SRT.

**Bench-scale biosorption and flotation test – influence of WAS on performance**

The purpose of this bench-scale test is to determine the influence of TF/SC WAS concentration on the biosorption and the flotation processes as a whole. Two TF/SC WAS and raw wastewater ratios of 5 and 10% (by volume) were selected, yielding doses of approximately 1.2 and 2.5 mg of WAS TSS per mg of wastewater sCOD, respectively, and compared with the control. These two ratios were chosen based on modeling of a WWTP that is under design to use surface wasting from the aeration basins to the HRBC system. The influent sCOD/ffCOD represented the wastewater before biosorption. The effluent sCOD/ffCOD was collected after the HRBC and flotation process. As shown in Figure 8, the sCOD and ffCOD removal increased with increasing amount of WAS. However, the results also showed sCOD and ffCOD were removed even without adding any WAS. After investigating the wastewater sampling point, it was found that the collected wastewater was mixed with in-plant solids return flows, which consisted of gravity thickener overflow, filtrate from gravity belt thickener, centrate, etc. The sCOD and ffCOD removals in the control most likely were due to the solids in these return flows. After subtracting the removals seen in the control (0% WAS), the actual sCOD removals observed for the 5 and 10% WAS ratios were 25 and 47 mg/L respectively, which were 14 and 27% removal based on an average influent sCOD of 175 mg/L. For the ffCOD removal, 16 mg/L and 30 mg/L ffCOD were removed for the 5 and 10% WAS ratios respectively which represented 11 and 21% removal based on an average influent ffCOD of 146 mg/L. These results indicate that absorption is directly proportional to the amount of WAS.

**CONCLUSIONS**

Both pilot and bench-scale test results showed that biosorption occurred using TF/SC WAS in the HRBC. Pilot test results revealed that a longer HRT is required when using TF/SC WAS to obtain sCOD removals comparable to other pilot studies or full-scale plant using AS WAS. However, bench-scale test results showed that using TF/SC WAS in HRBC can have a 68% higher normalized sCOD removal rate than using ASAS WAS, however, SAS mLE WAS appears to have much higher absorption. The results suggested that the biosorption capability of a WAS is not SRT dependent only. Although pilot test results showed the float material could have BMP as high as the primary sludge, operating the HRBC with DO higher than 0.5 mg/L or long HRT would reduce the BMP value. Oxidizing of organic matter stored in the microorganisms is suspected to be the reason for this occurrence. In contrast, the pilot test results revealed that sCOD removal was unstable when DO was lower than 0.5 mg/L in the HRBC with TF/SC WAS. Maintaining 0.5 mg/L DO concentration in the HRBC seems to be the optimal operating condition to obtain the benefits of good sCOD removal and high BMP in the float. The pilot, and bench-scale biosorption and flotation test results indicated a positive relationship between the sCOD/ffCOD removal and the added amount of WAS as the biosorbent. However, increasing WAS quantity in an actual treatment plant operation is usually not feasible because each plant manager would operate the plant to target a constant SRT.

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