Research Paper

Evaluation of treatment potential, biogas generation and sludge properties of an anaerobic claridigester

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ABSTRACT

The anaerobic process for the treatment of municipal and industrial wastewater has been in practice for over a century. Apart from treatment of wastewater, the process has the advantage of lower sludge and biogas production that can save energy. Application of this process in a primary clarifier in such a way that there is simultaneous digestion of primary settled sludge and organic removal from wastewater can be more advantageous in an aerobic treatment plant. The paper discusses the performance of such a primary claridigester at ambient temperature. With a single hydraulic retention time (HRT) of 4.5 h, the organic (chemical oxygen demand (COD) and biochemical oxygen demand (BOD)) removal efficiency was 36.3% and 34.6%, respectively. The biosolid production rate was 0.383 g VSS/g COD removed or 0.818 g VSS/g BOD$_3$ removed. However, biogas contains 80.8% methane and the COD mass balance revealed the loss of removed COD as 41.5% in the form of dissolved effluent from the claridigester. On account of sludge characterization, it was observed that nitrogen and zinc were present in highest concentration (2.55% and 1,776 mg/kg dry solids) and other nutrient and heavy metal parameters were within limits of not posing any risk of soil toxicity if disposed of for enrichment of soil.

Key words | anaerobic digestion, COD mass balance, methane production, primary sludge

INTRODUCTION

At the present time many aerobic processes of wastewater and sludge treatment are in practice and are successfully fulfilling the criteria set for the disposal of treated effluent to the environment. However the processes have some disadvantages like considerable installation, operation and maintenance costs, and high biosolid production. Also there is no provision in the aerobic process for energy recovery from wastewater. Anaerobic processes for treatment of wastewater and sludge digestion have the inherent benefit of cost effective treatment due to their potential for generation of biogas. The anaerobic process does not only facilitate energy recovery but also lowers the operational energy requirement compared to aerobic treatment with less requirement for reactor volume and more tolerance to higher organic loadings (Kato et al. 1994). The biogas generation may be different and depends on many operational factors. A biogas production rate of 0.18 to 0.22 m$^3$ kg$^{-1}$ chemical oxygen demand (COD) in an upflow anaerobic sludge blanket (UASB) reactor was reported by Khan et al. (2010, 2015), while Bodkhe (2009) and Krishna et al. (2008) reported biogas yield of 0.5 m$^3$/kg COD and 0.4 m$^3$/kg COD, respectively, in anaerobic treatment of municipal wastewater. Apart from this, biosolid production is also low in the anaerobic process which further reduces the cost associated with treatment and disposal of excess sludge produced. However, the anaerobic process is unable to meet the stringent effluent quality requirements (Singh et al. 1996; Takahashi et al. 2011).

In most aerobic wastewater treatment plants, a primary clarifier is installed before the secondary biological process.
in order to reduce the suspended solid and organic load to the aerobic process. The primary settled sludge in this way is generally digested with secondary settled sludge or disposed of for landfiling after dewatering and thickening (Han & Dague 1977; Bayr & Rintala 2012). The anaerobic digestion of primary sludge with secondary sludge facilitates only its stabilization and energy recovery without having any direct advantage over treatment of wastewater. But if the anaerobic digestion of the primary sludge is carried out in a primary clarifier itself, there will be an additional benefit of anaerobic treatment of wastewater. In this way the primary clarifier will involve three processes of primary settling, sludge digestion and partial treatment of wastewater simultaneously.

In order to enhance the functionality of a primary clarifier this way, an improved primary claridigester has been proposed. The basic processes occurring in the system have been studied intensively so far but the performance of the system as a whole requires evaluation. The variations in parameters like pH and alkalinity need to be assessed as they are stability-determining parameters of the anaerobic process. The biosolid production in the claridigester with real municipal wastewater will determine the reduction of suspended solid load. Subsequently, performance assessment of the claridigester for the removal of organics like biochemical oxygen demand (BOD), COD, nutrients and production of methane gas will decide the design of the secondary biological treatment process that will be combined with the claridigester.

For these requirements, the objective of this study was evaluation of a claridigester fed with municipal wastewater at ambient temperature. The evaluation was done in terms of biosolid, methane production, organics removal, nutrients and heavy metal characterization of settled sludge.

**MATERIALS AND METHODS**

**Reactor configuration and operation**

The schematic diagram of the experimental setup is shown in Figure 1. The system consists of a cylindrical shaped anaerobic claridigester having diameter 2.5 m and total height 6.3 m installed at a 33 million litres per day sequencing batch reactor (SBR) at Noida, India. The claridigester consists of a primary clarifier, a sludge digester and a gas holder designed in a single large tank. The upper portion functions as a clarifier and the bottom portion functions as a sludge digester. The wastewater was fed in a vertical mode from an L-shaped inlet pipe with a peristaltic pump. The supernatant from the upper portion of claridigester flows radially into the launder from where it comes out as effluent. Motor driven draft tube type mixers were provided at the bottom for mixing of the entire settled sludge to increase homogeneity of environmental conditions and maintain stable digestion of sludge. The rotation per minute (rpm) of the draft tube mixers was 1,450 rpm, overflow rate was 25 m³/m²/day and weir loading was 12.92 m³/day.m. Total solid retention time was 28 days. The gas was collected at the top of the claridigester in a cylindrical gas collector made of iron and its movement was guided by rails provided around its periphery. The produced biogas was measured by a gas flow meter (Gallus LNE 126, Itron China) and a moisture absorber (HYDINT HP-VS2) was provided before the flow meter to remove the water content present in the biogas.

The wastewater used in the study was screened with a total COD range from about 350 to 680 mg/L and soluble COD was in the range of 140 to 320 mg/L. The alkalinity of feed wastewater varied from 550 to 750 mg/L as CaCO₃.

The startup of an anaerobic reactor is generally achieved either by inoculation of seed sludge from an existing anaerobic treatment unit or by self-inoculation of the settled sludge after filling the reactor with wastewater (Draaijer et al. 1992, 1999).
In this study both methods were employed with slight modifications. Initially one quarter of the total volume of the claridigester was filled with sludge brought from a nearby SBR followed by filling up of the reactor with primary treated wastewater in batch mode and it was allowed to rest for two weeks. The process of filling was continued for 54 days. The mixing of settled sludge and inoculated sludge by draft tube mixers allows the development of a sludge bed at the bottom which provides a steady state environment for anaerobic digestion. Steady state conditions were considered to have been achieved when variation in percentage removal of COD on successive days was found insignificant. After that detailed analyses were carried out and the results discussed are inferred from the data obtained at this condition. In continuous mode the claridigester was operated at a single hydraulic retention time (HRT) of 4.5 hours and its evaluation was carried out for a period of 45 days. The average flow of wastewater was maintained as 85 m$^3$/day and organic loading rate in this mode was $2.8 \pm 0.6$ kg COD/m$^3$ d. The ambient temperature during the study period was in the range of 28–31°C. Some operating problems of gas escape with the effluent and moisture content in biogas were also resolved in the startup period by making a water lock in the outlet pipe and installing a moisture absorber before the gas flow meter, respectively.

**Analyses of wastewater and biogas**

Daily samples of influent and effluent were analyzed for pH (onsite), temperature (onsite), COD, total suspended solids (TSS), volatile suspended solids (VSS) and biogas. Ammoniacal nitrogen, phosphorus, BOD (5 days at 27°C), alkalinity and sulfate (onsite) were measured weekly. All the parameters were determined according to Standard Methods (American Public Health Association, APHA 1998). COD digestion was carried out in a digester (Model 45600, HACH, USA). Absorbance of the samples for determination of COD, ammonical nitrogen, and phosphorus were recorded at prescribed wave-lengths using spectrophotometer model DR 4000 (HACH, USA). Samples of biogas were collected in plastic gas bags. The gas composition (methane, carbon dioxide and sulfate) was determined using a gas chromatography-flame ionization detector (GC FID).

**Analysis of sludge characteristics**

The nutrient content (nitrogen, phosphorus and potassium) and heavy metals were analyzed in settled sludge of the claridigester. The sludge was dried and crushed to fine powder. One gram of dried sludge was digested with 4 ml of concentrated H$_2$SO$_4$ and 10 ml H$_2$O$_2$. After filtration the sample was diluted to 100 ml for analysis of nutrient content and heavy metals. The heavy metal analysis was done in an atomic absorption spectrophotometer (Thermo Fisher Scientific, USA).

**RESULTS AND DISCUSSIONS**

**pH and alkalinity**

pH variation in influent and effluent is of greater significance in anaerobic treatment of wastewater. Effluent pH values lower than the acidic limit is a result of washout of volatile fatty acids produced during acidogenesis. The average pH of the effluent was 7.7. The value being greater than the acidic limit shows the absence of fatty acid accumulation in the effluent and their effective utilization by methanogens.

Alkalinity is another parameter that defines the stability potential of anaerobic treatment. Higher alkalinity values are desirable as it gives a better support against a drop in pH due to fatty acids increase (Metcalf & Eddy Inc. 2003a). During this study the average influent total alkalinity slightly decreased from 699 mg/L as CaCO$_3$ to 658 mg/L as CaCO$_3$. The little drop in alkalinity was due to the formation of ammonium bicarbonates from the combination of ammonia and carbon dioxide, released during biodegradation, which compensates the decrease in alkalinity due to fatty acids.

**Biosolid production and suspended solid removal**

Compared to aerobic treatment of wastewater, anaerobic treatment has the benefit of lesser biosolid production (Seghezzo et al. 1998). Estimation of biosolid production helps in the design of sludge handling facilities. Apart from digestion of primary sludge in the claridigester, there was wastage of biosolids in the bottom in the sludge bed also...
which was quantified by estimating the volatile solids in it. The wastage rate of biosolids was estimated from the VSS content of the wasted sludge. The net rate of biosolid production can be therefore estimated after deducting the VSS content of wasted sludge and accumulated sludge from the total difference of VSS in influent and effluent. The biosolid production rate obtained in this way was 0.383 g VSS/g COD removed or 0.818 g VSS/g BOD$_3$ removed.

Since there was simultaneous settling and digestion of primary sludge in the claridigester, efforts were made to calculate the biosolid production rate as this will also determine the rate of sludge wasting in actual practice. The biosolid production was calculated according to the approach adopted by Yoo et al. (2012). Due to absence of any recirculation, the rate of biosolid production can be directly obtained after deducting the VSS content of wasted sludge from the total difference of VSS in influent and effluent. The biosolid production rate obtained by this method was 0.383 g VSS/g COD removed or 0.818 g VSS/g BOD removed. A value of 0.031 g VSS/g COD or 0.049 g VSS/g BOD for an anaerobic reactor has been reported by Yoo et al. (2012). The lower biosolid production may be due to presence of less rapidly biodegradable volatile solid content in the raw wastewater. These solids degrade at a slower rate to produce biosolids and their presence is greater in raw sewage than primary effluent. The wastewater treated in the reported study was primary effluent whereas in our study raw wastewater was treated which might have resulted in low biosolid production.

The variation of TSS and VSS is shown in Figure 2. The influent TSS varies from 260 to 383 mg/L while as effluent TSS was in the range of 146–206 mg/L. The average removal of suspended solids in the claridigester was 52.4%. Influent and effluent VSS concentration varied between 116 mg/L–213 mg/L and 56 mg/L–128 mg/L respectively, with an average removal of 49.6% (Table 1). The efficiency was comparable to a conventional primary settling unit but this much removal along with biogas generation and COD reduction is an economic and sustainable option for upgradation of an aerobic treatment system for resource recovery.

**Organic and nutrient parameters**

The organic removal efficiency of the claridigester is summarized in Table 1 and the profile of COD is shown in Figure 3. As compared to conventional anaerobic systems of wastewater treatment, the organic removal from wastewater in the claridigester was less. The average COD and BOD removal efficiency was only 36.3% and 34.6%,
respectively. Removal efficiency of particulate COD is 43% and soluble COD removal was 15.4%. This increase in the removal of particulate COD signifies the contribution of sedimentation in removal of organic content which is also justified by relatively larger TSS and VSS removal (52.4% and 49.6%, respectively) than COD. COD of municipal wastewater usually varies over a wide range which was also observed in our study. The COD in influent and effluent ranges from 332 mg/L–680 mg/L and 179 mg/L–413 mg/L respectively. It was observed that the effluent also varies in the same manner (Figure 3) by which it seems like the organic removal ability of the claridigester is little affected by variation in organic content. This may be because a major portion of COD is removed by settling.

The % BOD and TSS removal in a conventional primary clarifier varies between 38.5% and 60.6%, respectively, at 3-h detention time. Evaluation of BOD and TSS removal in four actual working plants was also observed. The percentage removal was 24–40% and 38.5–52%, respectively, which was consistent with that observed in the claridigester.

The consistency of sludge in the claridigester was 5 ± 0.8%. The primary sludge consistency in a conventional primary clarifier also varies from 5 to 9% with a typical value of 6% (Metcalf Eddy Inc. 2003). This showed that there were extra advantages of a primary clarifier in terms of BOD, TSS removal and sludge consistency, which were achieved along with production of biogas in the claridigester. The removal of nitrogen and phosphorus was quite low. The average value of total kjeldahl nitrogen (TKN) and orthophosphate in influent was 63.7 mg/L and 4.2 mg/L, respectively, which decreased to 59.1 mg/L and 4 mg/L, respectively, in effluent of the claridigester. This small removed portion may be the dissolved nitrogen and phosphorus contained in the water content of settled sludge and fulfills the nutrient requirement of carrying out its anaerobic digestion. The nitrogen content in influent wastewater was enough also to provide buffering capacity to the claridigester.

### Biogas generation

Daily specific biogas production in terms of m³CH₄/kg COD₇ is shown in Figure 4 and the composition of biogas samples was determined by GC fitted with an FID column. The methane fraction in the biogas from the claridigester was 80.8% and the carbon dioxide fraction was 8.1%. Sulfur dioxide content in the biogas was below the detection limit (5 ppm) and hydrogen sulfide was 26 ppmv (0.0026%). A comparable methane fraction of 70% was also observed by Bodkhe (2009) during anaerobic treatment of wastewater in an anaerobic baffled reactor (ABR). The higher percentage observed may be due to the greater treatment capacity of the claridigester which was 85,000 L/d, while it was 5.33 L/d in the reported study. Although the carbon dioxide percentage was less than expected, this might be a

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Inlet</th>
<th>Outlet</th>
<th>Removal (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>8.0</td>
<td>7.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ORP*</td>
<td>mV</td>
<td>–149.5</td>
<td>–94</td>
<td></td>
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<tr>
<td>Alkalinity</td>
<td>mg/L</td>
<td>699 ± 116.3</td>
<td>658 ± 124.1</td>
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<tr>
<td>Total COD</td>
<td>mg/L</td>
<td>523 ± 101.7</td>
<td>330 ± 70.9</td>
<td>36.3</td>
</tr>
<tr>
<td>Soluble COD</td>
<td>mg/L</td>
<td>200 ± 71.6</td>
<td>164 ± 42.7</td>
<td>15.4</td>
</tr>
<tr>
<td>Total BOD</td>
<td>mg/L</td>
<td>255 ± 70</td>
<td>162.5 ± 27.3</td>
<td>34.6</td>
</tr>
<tr>
<td>Soluble BOD</td>
<td>mg/L</td>
<td>129 ± 43.1</td>
<td>81 ± 4.2</td>
<td>37</td>
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<tr>
<td>TSS</td>
<td>mg/L</td>
<td>329 ± 44.2</td>
<td>159 ± 21.4</td>
<td>52.4</td>
</tr>
<tr>
<td>VSS</td>
<td>mg/L</td>
<td>154 ± 30.5</td>
<td>80 ± 22.8</td>
<td>49.6</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>mg/L</td>
<td>369 ± 18.7</td>
<td>328 ± 10.7</td>
<td></td>
</tr>
<tr>
<td>S²⁻</td>
<td>mg/L</td>
<td>23.5 ± 0.7</td>
<td>31 ± 1.4</td>
<td></td>
</tr>
</tbody>
</table>

*Oxidation reduction potential.

Figure 3 | Changes in influent and effluent total COD and its percentage removal.
consequence of its higher relative solubility. Yoo et al. (2012) also observed a fraction of 9–10% CO₂ during anaerobic treatment in an anaerobic fluidized membrane reactor. The lower hydrogen sulfide content was due to the lower value of the COD/SO₄ (1.4) ratio which suppresses the stripping of sulfide from the liquid phase (Arceivala & Asolekar 2007a).

The average specific methane production was 2.21 m³ CH₄/day or 0.146 m³ CH₄/kg CODₜ. The yield was comparable or slightly lesser than those observed by Khan et al. (2015) (0.22 m³ kg⁻¹ COD) and Bodkhe (2009) (0.34 m³ CH₄/kg COD) who also treated domestic wastewater anaerobically. However, the methane production was lower than the theoretical value of 0.35 m³ CH₄/kg CODₜ given by Metcalf & Eddy Inc. (2003c). These lower values may be due to biogas escape along with the effluent, COD removal by sulfate-reducing bacteria and unavoidable biogas measurement limitations. An escape of more than 50% of CH₄ was observed by Lettinga et al. (1993) with treated effluent while treating domestic wastewater. Specific methane generation in the claridigester was 0.05 L g⁻¹ VS d⁻¹ to 0.45 L g⁻¹ VS d⁻¹. The results were consistent with those reported by Gomez et al. (2006) and Bujoczek et al. (2010). They reported a range of 0.2–0.5 L g⁻¹ VS d⁻¹ and 0.1–0.5 L g⁻¹ VS d⁻¹ respectively.

COD mass balance

In order to assess the recovery of methane from the claridigester a COD mass balance was carried out (Figure 5). The various conversion coefficients which were adopted in performing the balance were according to Arceivala & Asolekar (2007b). Total COD removal was 16.4 kg COD/day. Out of the total COD removed, the COD equivalent of produced methane was 6.31 kg/day, which was calculated after adopting an equivalent coefficient of 2.86 g COD/L CH₄. This consisted of 38.5% of removed COD. The dissolved methane in effluent was calculated by assuming a methane content of 0.028 m³/m³ effluent (Arceivala & Asolekar 2007b) in it. The calculated dissolved methane content was converted to COD which was equal to 6.8 kg COD/day (41%) of total removed COD. The COD utilized in biosolid production was 1.87 kg COD/day which consisted of 11% of total COD removed. The COD reduction by sulfate-reducing bacteria calculated after assuming a coefficient of 0.67 kg COD utilized/kg sulfate (Arceivala &
Asolekar (2007a) was 2.35 kg COD/day or 14% of removable COD. A difference of 5% was found in observed and calculated values of COD. Due to the large standard deviation in influent characteristics in raw sewage, a good agreement of COD consumed in various processes is difficult. This small difference can be attributed to the inherent imprecise nature of coefficients. Singh & Viraraghavan (1998) reported a similar range of 35–45% conversion of COD into methane by methanogens for municipal wastewater. Polprasert et al. (1992) also observed that 31–55% of total COD entering an ABR was converted to methane while treating wastewater from a slaughter house.

Characterization of primary settled sludge

The characterization of settled sludge is summarized in Table 2. The average mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) concentration of settled sludge of the claridigester was 49,802 mg/L and 20,189 mg/L respectively. The ratio of MLVSS and MLSS after 18 days of startup was 0.43 and it decreased to 0.38 after 35 days of operation. This indicates the increase in VSS destruction in the settled sludge which was also justified by the increase in biogas production from 2.34 m³/day to 2.73 m³/day in the same period.

In order to assess the soil improvement potential of the sludge produced in the claridigester, organic, nutrient and heavy metal characterization of the dried sludge sample was carried out (Table 2). The organic content (COD) of the sludge was 29,340 mg/L. This high organic content can improve the water retaining capacity and structure of soil especially if disposed of in the form of cakes. The percentage of three significant nutrients, i.e. nitrogen, phosphorus and potassium, was 2.55, 0.35 and 0.28, respectively. The percentage of phosphorus in the sludge was lower than 1.34%, the value common in sewage sludge from wastewater treatment plants of India. This was due to negligible removal of phosphorus in the claridigester while in other treatment plants phosphorus is removed by its accumulation in final settled biomass. On the contrary, the nitrogen content was equivalent to the characteristics of sludge produced in India and hence justifies the suitability of sludge as a nitrogen enrichment substance to soil. A similar comparison can be made with the respective values of 2.53, 1.05 and 0.74% reported by Wang (1997), in the sewage sludge from wastewater treatment plants of china.

Among various heavy metals, zinc (Zn) was present in the highest concentration (1,776 mg/kg dry solid) which is usual in anaerobic sludge. Cadmium (Cd) was present in the lowest (0.19 mg/kg dry solid) concentration followed by chromium (Cr), copper (Cu) and iron (Fe) in ascending order. These heavy metals such as Cu, Zn, and Cr etc., being essential nutrients for plant growth, can be supplied to low fertile soil through disposal of sewage sludge. The values are almost same as those found in sludge from other treatment plants in India (Nandakumar et al. 1998). This is because, as in our study, there is no sludge treatment in other wastewater treatment plants that can remove heavy metals particularly.

Table 2 | Organic, nutrient and heavy metal characterization of primary settled sludge of the claridigester

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLSS</td>
<td>mg/L</td>
<td>49,801 ± 8,473</td>
</tr>
<tr>
<td>MLVSS</td>
<td>mg/L</td>
<td>20,188 ± 1,671</td>
</tr>
<tr>
<td>COD</td>
<td>mg/L</td>
<td>29,340</td>
</tr>
<tr>
<td>Nitrogen (N)</td>
<td>% (g/kg dry solids)</td>
<td>2.55</td>
</tr>
<tr>
<td>Phosphorus (P)</td>
<td>% (g/kg dry solids)</td>
<td>0.35</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>% (g/kg dry solids)</td>
<td>0.28</td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>mg/kg dry solids</td>
<td>1,776</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>mg/kg dry solids</td>
<td>189</td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
<td>mg/kg dry solids</td>
<td>0.19</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>mg/kg dry solids</td>
<td>8.68</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>mg/kg dry solids</td>
<td>140</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>mg/kg dry solids</td>
<td>509</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>mg/kg dry solids</td>
<td>431</td>
</tr>
</tbody>
</table>

*Nandakumar et al. (1998).

CONCLUSION

In this paper the performance of a claridigester was discussed which can replace existing primary clarifiers with the
additional advantage of energy recovery and partial organic removal. The claridigester treating screened domestic municipal wastewater at ambient temperature of 28–31 °C and HRT of 4.5 hours had 36% total COD and 52% suspended solid removal efficiency with little removal of nitrogen and phosphorus. The methane fraction in biogas was 80.8% and the yield was 2.21 m³ CH4/day or 0.146 m³CH4/kg COD. COD mass balance shows loss of a significant portion of removed COD as dissolved effluent. The settled sludge is safe for disposal to land as it contains enough nitrogen and heavy metals are also comparable to those found in sludge wasted from conventional treatment plants. The study can be useful in designing, operation and installation of such a system in a new sewage treatment plant or in an existing wastewater treatment facility after required retrofitting.

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