  Water Science & Technology—WST | 57.8 | 2008

# Treatment of low and medium strength sewage in a lab-scale gradual concentric chambers (GCC) reactor

L. Mendoza, M. Carballa, L. Zhang and W. Verstraete

## ABSTRACT

One of the major challenges of anaerobic technology is its applicability for low strength wastewaters, such as sewage. The lab-scale design and performance of a novel Gradual Concentric Chambers (GCC) reactor treating low (165 ± 24 mg COD/L) and medium strength (550 mg COD/L) domestic wastewaters were studied. Experimental data were collected to evaluate the influence of chemical oxygen demand (COD) concentrations in the influent and the hydraulic retention time (HRT) on the performance of the GCC reactor. Two reactors ($R_1$ and $R_2$), integrating anaerobic and aerobic processes, were studied at ambient (26°C) and mesophilic (35°C) temperature, respectively. The highest COD removal efficiency (94%) was obtained when treating medium strength wastewater at an organic loading rate (OLR) of 1.9 g COD/L·d (HRT = 4 h). The COD levels in the final effluent were around 36 mg/L. For the low strength domestic wastewater, a highest removal efficiency of 85% was observed, producing a final effluent with 22 mg COD/L. Changes in the nutrient concentration levels were followed for both reactors.

**Key words** | anaerobic digestion, developing countries, reactor configuration, sewage, temperature

**L. Mendoza**
Experimental Reproduction Centre (CEYSA),
Agricultural Faculty,
Technical University of Cotopaxi,
Latacunga,
Ecuador
E-mail: *lauramen_2000@yahoo.com*

**M. Carballa**
**L. Zhang**
**W. Verstraete**
Laboratory of Microbial Ecology and Technology (LabMET),
Ghent University,
Coupure Links 653,
B-9000 Ghent,
Belgium
E-mail: *willy.verstraete@UGent.be*; *marta.carballa@ugent.be*; *lezhanghua@hotmail.com*

## INTRODUCTION

Wastewater treatment technologies for developing countries often remain ineffective due to economical and technical problems. Ecuador is a country geographically crossed by rivers and surface watercourses. These water sources have traditionally served to provide the basic water needs for most of the inhabitants of rural areas. Most industrial and nearly all the domestic wastewaters of the country are disposed directly to the rivers crossing or surrounding the cities. Statistics show that only 5% of the discharges at national level are treated previously to be disposed of. The present study deals with the biological treatment of the discharges of Latacunga, a small Ecuadorian city with a mean ambient temperature of 16°C. The water consumption for the urban area of the city is about 300 L/capita·d (Consulta solutions 1995), but this rate decreases considerably for the rural districts (80–120 L/capita·d). A Gradual Concentric Chambers (GCC) reactor, a simple set-up integrating anaerobic and aerobic compartments, was used. Research studies treating domestic wastewaters using anaerobic reactors have been reported (Van der Last & Lettinga 1992; Van Haandel & Lettinga 1994; Langenhoff & Stuckey 2000). The objective of the present study was to evaluate the performance of the GCC reactor treating low and medium strength sewage. The influence of temperature, aeration and organic loading rate (OLR) applied on chemical oxygen demand (COD) removal efficiency has been examined.

doi: 10.2166/wst.2008.093

## MATERIALS AND METHODS

### GCC reactor design

Two GCC reactors ($R_1$ and $R_2$), consisting of three different sized chambers assembled to create anaerobic and aerobic conditions, were constructed using common glass (silicate) and plastic material. Figure 1 shows a scheme of these continuously fed reactors and their experimental dimensions are presented in Table 1. $R_2$ was equipped with two additional connections at the top of the headspace to allow the recycling of the anaerobic effluent (Cole Parmer-Masterflex, Serial 364599) and to avoid biogas clogging in the sludge. To aerate the content of the aerobic compartment of the reactors, a low energy submersible pump (Tialu, 12 W, HJ 921), which turned only the upper water layers, was installed. Besides, this compartment was filled with gravel to improve anaerobic biota filtration and settling. A conventional biogas collection through water displacement was used.

## Reactor start-up and operation

The anaerobic compartments of both reactors were inoculated with 250 mL of anaerobic sludge (18 g VSS/L) and the reactors were further filled with tap water. $R_1$ was operated at 26.0 ± 1.5°C and $R_2$ at 35.0 ± 1.0°C. The feeding was stored in 77 L polyethylene tanks and pumped into the anaerobic compartment of the reactors using a peristaltic pump (Cole Parmer-Masterflex, Model 7520-10, Serial 419507). The recycling flow rate of $R_2$ was adjusted to 7 mL/min to avoid sludge washout (Tchobanoglous & Burton 1991). Five stages of operation were carried out according to the type of influent treated, temperature and the use or not of aeration. In each stage, the feeding flow rates were increased stepwise provided that the COD removal efficiency reached 70% in order to test the maximum performance of the GCC reactors in terms of COD removal efficiency.

## Wastewater characteristics

Two types of wastewater were used: (1) a low strength wastewater (165 ± 24 mg COD/L) consisting of black domestic wastewater from toilets and bathroom household

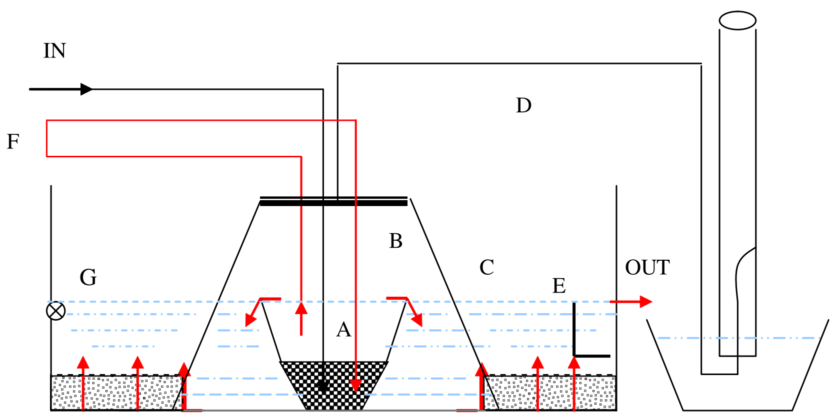


**Figure 1** | Schematic diagram of the GCC reactor. A: Anaerobic compartment; B: Headspace compartment; C: Aerobic compartment, D: Gas collection pipeline; E: Effluent pipeline; F: Anaerobic effluent recycling pipeline; G: Aeration pump. Arrows indicate the wastewater course.

**Table 1** | Dimensions of the lab-scale GCC reactors

| | Reactor 1* | | | Reactor 2† | | |
|---|---|---|---|---|---|---|
| Compartment | A | B | C | A | B | C |
| Operational volume (L) | 2.1 | 5.4‡ | 27.5 | 2.0 | 4.7‡ | 19.0 |
| Height (mm) | 230 | 360 | 300 | 195 | 280 | 300 |
| Diameters (mm) | 85–130 | 150–227 | 425–500 | 110–120 | 185–215 | 307–430 |
| Headspace (L) | – | 2.7 | – | – | 1.9 | – |
| Material | Glass | Glass | Plastic | Glass | Plastic | Plastic |

*,†Total $R_1$ and $R_2$ volumes: 70 L (Liquid volume: 35 L) and 40 L (Liquid volume: 25.7 L), respectively.
‡Liquid below headspace minus volume of A.

use (Table 2); and, (2) a synthetic wastewater using sodium acetate as carbon source at a theoretical COD concentration of 550 mg/L, to simulate a medium strength wastewater. This solution was supplemented with essential nutrients and trace elements to obtain a balanced feeding solution (COD:N:P of 100:1.25:0.25).

### Analytical methods

Physical-chemical parameters were determined according to *Standard Methods for the Examination of Water and Wastewater* (1992).

## RESULTS AND DISCUSSION

Table 3 shows of the operational parameters of both reactors at each stage of operation.

### COD removal

In phase I, treating influent COD concentrations of ca 148 ± 20 mg/L (OLR and HRT ranging 0.4–1.5 g COD/L·d and 3–9 h, respectively), the maximum COD removal efficiency observed was 77% (OLR of 0.8 g COD/L·d). Aiyuk *et al.* (2004) treated an influent of 140 mg COD/L in an upflow anaerobic sludge bed (UASB) reactor at OLR of 0.4–0.7g COD/L·d, (HRT of 5–10 h) achieving COD removal efficiencies of 55 and 60%, respectively. Higher COD elimination was obtained in phase II (81–93%), when medium strength wastewater was treated at OLRs of 1.9–4.2 g COD/L·d (HRT of 3–7 h) and with aeration. It was also observed that COD elimination decreased at OLRs higher than 1.9 g COD/L·d.

In phase III, treating medium strength wastewater at OLRs of 1.8–4.5 g COD/L·d and no aeration of the effluent, the maximum COD removal efficiency achieved was 76% (OLR: 1.8 g COD/L.d; HRT = 7.3 h). Similarly to phase II, COD elimination decreased when high OLRs were applied, with a significant decrease in the COD removal efficiency (40%) being observed at an OLR of 4.5 COD/L·d. This low elimination coincided with high suspended solids content in the effluent of the reactor, suggesting that sludge washout occurs at HRTs lower than 2.7, as well as a limited contact time for physical and biological processes (Carrhá 2004). In phase IV, when aeration was included, COD removal efficiencies increased up to 82–94%. In addition, these efficiencies increased at higher OLRs (1.8–3.0 g COD/L·d; HRTs of 4–7 h). This fact demonstrates the positive influence of aeration on COD removal efficiencies, increasing its elimination from ca 72 ± 3% (phase III) to 90 ± 4% (phase IV) within the OLR range 1.8–3.0 g COD/L·d. In contrast, comparing the COD removal efficiency of this phase (90 ± 4%) with that of phase II at OLRs of 1.9–3.4 g COD/L·d (87 ± 4%), it can be concluded that temperature range used in this study (26–35°C) did not affect significantly COD elimination.

In phase V, when low strength wastewater was treated at OLR of 0.2–1.0 g COD/L·d with aeration, the COD removal efficiencies achieved were 75–85%. Similarly to phase IV, COD elimination increased at higher OLRs. Comparing with the experiment of phase IV at OLR of 1.8 g COD/L·d (82 ± 2%), it can be concluded that lower influent COD concentrations gave rise to lower COD removal efficiencies. Besides, when comparing with the COD elimination obtain in phase I (OLR of 0.4–1.0 g COD/L·d), i.e. 71 ± 5%, it can be confirmed that the

**Table 2** | Physical-chemical characteristics of the crude sewage (September 2006–February 2007)

| Parameter | Value | n* |
|---|---|---|
| Temperature (°C) | 17.3 ± 1.0 | 18 |
| pH | 7.3 ± 0.1 | 30 |
| Alkalinity (mg $CaCO_3$/L) | 22.6 ± 0.5 | 5 |
| CODt (mg/L) | 165 ± 24 | 25 |
| CODs (mg/L) | 136 ± 18 | 12 |
| $BOD_5$ (mg/L) | 102 ± 19 | 7 |
| TKN (mg/L) | 40.5 | 5 |
| $NH_4^+$—N (mg/L) | 6.5 ± 1.2 | 20 |
| $NO_2^-$—N (mg/L) | 0.04 ± 0.02 | 9 |
| $NO_3^-$—N (mg/L) | 6.5 ± 4.7 | 25 |
| $PO_4^{3-}$—P (mg/L) | 5.0 ± 1.8 | 6 |
| Sulfate (mg/L) | 5.8 ± 1.3 | 3 |
| TSS (mg/L) | 587 ± 0.1 | 10 |
| VSS (mg/L) | 273 ± 0.1 | 10 |
| Total coliform (CFU/100mL) | $2.9 \times 10^4$–$1.0 \times 10^7$ | 3 |
| Faecal coliform (CFU/100mL) | $1.5 \times 10^2$–$1.0 \times 10^4$ | 3 |

*n: number of samples.

**Table 3** | Performance data on GCC reactors for COD removal efficiencies

| Experiment | Temperature (°C) | HRT* (h) | OLR† (g COD/L·d) | CODi (mg/L) | CODe (mg/L) | COD removal (%) |
|---|---|---|---|---|---|---|
| Phase I, $R_1$: Low strength wastewater. No effluent aeration | | | | | | |
| 1 | 26 | 7.5/125 | 0.4 | 115 | 41 | 64 |
| 2 | 26 | 9.2/153 | 0.4 | 138 | 42 | 69 |
| 3 | 26 | 5.9/98 | 0.5 | 138 | 35 | 74 |
| 4 | 26 | 3.9/65 | 0.8 | 138 | 31 | 77 |
| 5 | 26 | 3.5/58 | 1.1 | 167 | 49 | 70 |
| 6 | 26 | 3.0/50 | 1.3 | 167 | 49 | 70 |
| 7 | 26 | 2.7/45 | 1.5 | 170 | 50 | 69 |
| Phase II, $R_1$: Medium strength wastewater. Effluent aeration | | | | | | |
| 8 | 26 | 6.6/110 | 1.9 | 550 | 38 | 93 |
| 9 | 26 | 5.4/90 | 2.4 | 550 | 63 | 89 |
| 10 | 26 | 3.8/63 | 3.4 | 550 | 87 | 84 |
| 11 | 26 | 3.4–56 | 4.2 | 550 | 103 | 81 |
| Phase III, $R_2$: Medium strength wastewater. No effluent aeration | | | | | | |
| 12 | 35 | 7.3/94 | 1.8 | 550 | 134 | 76 |
| 13 | 35 | 5.3/68 | 2.2 | 550 | 139 | 74 |
| 14 | 35 | 4.8/61 | 2.7 | 550 | 164 | 70 |
| 15 | 35 | 4.4/56 | 3.0 | 550 | 179 | 67 |
| 16 | 35 | 2.4/30 | 4.5 | 550 | 328 | 40 |
| Phase IV, $R_2$: Medium strength wastewater. Effluent aeration | | | | | | |
| 17 | 35 | 7.3/94 | 1.8 | 550 | 100 | 82 |
| 18 | 35 | 5.3/68 | 2.5 | 550 | 50 | 91 |
| 19 | 35 | 4.8/61 | 2.7 | 550 | 43 | 92 |
| 20 | 35 | 4.5/58 | 2.9 | 550 | 41 | 92 |
| 21 | 35 | 4.4/56 | 3.0 | 550 | 36 | 94 |
| Phase V, $R_2$: Low strength wastewater. Effluent aeration | | | | | | |
| 22 | 35 | 19.5/250 | 0.2 | 119 | 30 | 75 |
| 23 | 35 | 8.9/114 | 0.4 | 146 | 30 | 79 |
| 24 | 35 | 5.3/68 | 0.6 | 146 | 27 | 81 |
| 25 | 35 | 4.4/56 | 0.8 | 146 | 25 | 82 |
| 26 | 35 | 3.8/49 | 1.0 | 165 | 30 | 82 |
| 27 | 35 | 3.4/43 | 1.0 | 146 | 22 | 85 |

*1st value: based on anaerobic compartment volume. 2nd value: based on total reactor volume.
†Based on anaerobic compartment volume.
HRT: hydraulic retention time; OLR: organic loading rate; $COD_i$: influent total chemical oxygen demand; $COD_e$: effluent total chemical oxygen demand.

combined effect of aeration and temperature increased the COD removal.

By comparing the COD removal efficiencies of experiments 22 and 23 (75 and 79%, respectively), it seems that 9 hours could be an adequate HRT to achieve COD removal efficiencies higher than 75% in the GCC reactor treatment low strength wastewater (around 150 mg COD/L) at 35°C. Using a similar experimental design, Carrhá (2004) demonstrated that the UASB reactor can efficiently treat sewage with a concentration as low as 200 mg COD/L at a HRT as low as 2 hours. The maximum COD removal efficiency using sewage was achieved at influent concentrations exceeding 300 mg/L and a HRT of 4 hours, which corresponds with the results obtained in the present work.

As expected, a permanent biogas bubbling was observed in the headspace of $R_2$, due to the anaerobic recycling. However, some of the biogas still remained dissolved in the liquid phase of the anaerobic fluid. Although the influence of recycling on COD removal efficiencies was not studied in detail, it appeared negligible due to the low up flow velocity applied.

## Nutrients removal

The $NH_4^+$—N level in both low and medium strength sewage was 6.5 ± 1.2 mg $NH_4^+$—N/L (Figure 2). Aeration and no aeration of the effluents decreased this level to 0.3 ± 0.3 and 2.2 ± 1.3 mg $NH_4^+$—N/L, respectively, for the low strength wastewater, while for the medium strength wastewater, the ammonium nitrogen concentrations decreased to 3.6 ± 2.6 and 5.4 ± 0.7 mg $NH_4^+$—N/L in the aerated and non-aerated effluents, respectively. These results suggest that, on one hand, nitrification occurs in less extent when higher COD concentrations are present in the influent; and on the other hand, recirculation of the upper water layers of the aerobic compartment enhanced ammonium removal up to 95 and 46%, for low and medium strength wastewater, respectively.

Accordingly, nitrate production was higher during the treatment of low strength wastewater than of medium strength sewage (Figure 2b). The initial nitrate concentrations in the crude sewage were 6.5 ± 4.7 mg $NO_3^-$—N/L and they increased up to 6.8 ± 0.7 and 11.7 ± 6.8 mg $NO_3^-$—N/L in the non-aerated and aerated effluent, respectively (Figure 2b). The initial nitrate levels in the synthetic medium strength wastewater were negligible, and they slightly increased up to 2.6 ± 0.1 and 3.0 ± 1.1 mg $NO_3$—N/L in the non-aerated and aerated effluent, respectively.

Orthophosphates analyses were conducted only during phase V, indicating an average $PO_4^{3-}$—P removal efficiency of 42% (data not shown). These values are within the range of those reported by Cao *et al.* (2006) for phosphorus removal in anaerobic processes.

## Solids elimination

The average VSS concentration in the reactors effluents was 13.5 mg/L, which accounts for around 75% of the TSS of the crude sewage (Table 2). Overall, the total solids (TS) and VSS removal efficiencies obtained when crude sewage (low strength wastewater) was treated were 27 and 95%, respectively (data not shown). Given the structure and design of the reactor and considering the low velocity applied for wastewater recirculation, it is quite likely that part of the solids removal is due to physical deposition.

## Total and fecal coliforms elimination

During low strength wastewater treatment, total and faecal coliforms showed a removal of more than 2 log (data not shown); however, *E. coli* did not show any significant removal.

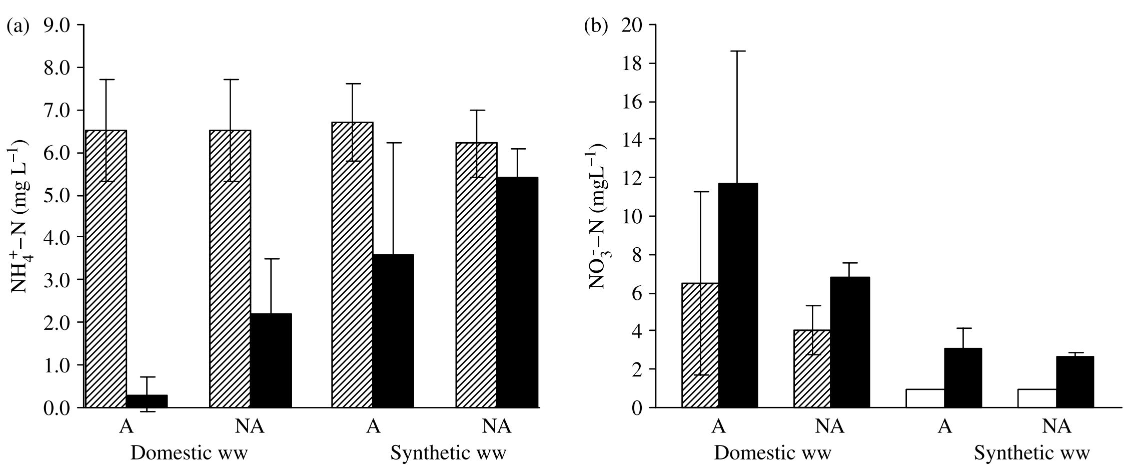


**Figure 2** | a) Ammonium nitrogen levels in the GCC reactors. b) Nitrate concentrations in the GCC reactors. Stripped bars: influent. Solid bars: effluent. Empty bars: not detectable. Domestic ww: low strength wastewater. Synthetic ww: medium strength wastewater. A: aeration. NA: no aeration.

## CONCLUSIONS

The GCC reactors were capable of treating successfully low and medium strength sewage at 26 and at 35°C and at OLR varying from 0.2 to 4.5 g COD/L·d (HRT of 2.4–19.5 h). The highest COD removal efficiencies were achieved when medium strength wastewater was treated at 35°C and with aeration, i.e. 85–94%. However, the highest ammonium elimination was obtained when low strength wastewater was used and, once again, when aeration was applied. The aerobic step promoted a increase of 20% in COD removal, also evidenced by the absence of odor in the effluents, and enhanced the nitrification process.

This simple reactor design offers a great potential for lowering the treatment costs of sewage treatment in tropical and subtropical countries, but maintaining the treatment efficiency. This fact warranted that this approach is currently tested at pilot scale.

## ACKNOWLEDGEMENTS

The financial support of the Belgian Technical Cooperation and the Technical University of Cotopaxi is greatly appreciated. The authors gratefully acknowledge the Spanish Ministry of Education and Science for financing the postdoctoral grant (EX2006-0963).

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