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RESEARCH ARTICLE

Technical and economic feasibility of gradual concentric chambers reactor for sewage treatment in developing countries

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Abbreviations:
COD: chemical oxygen demand
DO: dissolved oxygen
GCC: gradual concentric chambers
HRT: hydraulic retention time
I.E.: inhabitant equivalent
SND: simultaneous nitrification-denitrification process
TAN: total ammonia nitrogen
TKN: total kjeldahl nitrogen
TON: total oxidised nitrogen
TSS: total suspended solid
UASB: upflow anaerobic sludge bed
VFA: volatile fatty acids
VSS: volatile suspended solids

A major challenge in developing countries concerning domestic wastewaters is to decrease their treatment costs. In the present study, a new cost-effective reactor called gradual concentric chambers (GCC) was

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designed and evaluated at lab-scale. The effluent quality of the GCC reactor was compared with that of an upflow anaerobic sludge bed (UASB) reactor. Both reactors showed organic matter removal efficiencies of 90%; however, the elimination of nitrogen was higher in the GCC reactor. The amount of biogas recovered in the GCC and the UASB systems was 50% and 75% of the theoretical amount expected, respectively, and both reactors showed a slightly higher methane production when the feed was supplemented with an additive based on vitamins and minerals. Overall, the economical analysis, the simplicity of design and the performance results revealed that the GCC technology can be of particular interest for sewage treatment in developing countries.

Efficient wastewater treatment technology is costly, basically due to energy requirements, *i.e.* aeration, and chemical needs, bringing about high operational costs. Industrialized high income countries have the means and knowledge to invest in highly sophisticated and efficient wastewater treatment plants. However, developing countries lack capital for investment, technologies adapted to the climate conditions and skilled labour force to treat sewage. Aiyuk et al. (2004) discussed the need to develop reliable technologies to treat domestic wastewater in the developing world, which are mostly tropical regions. El-Gohary and Nasr (1999) also pointed out that in developing countries, where capital and skills are not readily available, solutions to wastewater treatment should preferably be low-technology oriented.

The efforts to get effective designs in terms of simple and non-sophisticated equipment, low capital investment costs and low operating and maintenance costs have resulted into the so-called low investment sewage treatment (LIST) concept. The overall capex and opex costs should not exceed 30 € per inhabitant equivalent (I.E.) per year (Sandino, 2007). The present work evaluates a novel Gradual Concentric Chambers (GCC) reactor, which combines anaerobic and aerobic treatment by using a simple assemblage of inexpensive vessels. One of the most attractive points is that no heavy material carrying walls are needed, except for the outer compartment. The performance of the GCC reactor treating medium-strength sewage has been compared with a well known and efficient technology, the Upflow Anaerobic Sludge Bed (UASB) reactor, in terms of organic matter and nutrient removal and biogas production. An approximate cost analysis of GCC reactor is also presented in order to evaluate its application at a decentralized level in municipalities of low income countries.

MATERIALS AND METHODS

Experimental set-up

The lab-scale GCC reactor set-up consisted of 3 containers, arranged up-side right and down to create the different compartments (Table 1, Figure 1). The influent was pumped to the bottom of the anaerobic compartment. The concentric distribution of the containers allowed the effluent of the anaerobic compartment to enter the outer aerobic compartment. Deflectors were used to increase the contact between the sludge and the mixed liquor as well as to decrease the sludge wash out. The biogas was collected by volume displacement in a graduated glass column immersed in acidified water (pH < 4, 2N HCl) to prevent CO_2 dissolving. A 5 l UASB reactor, as described by Kalogo et al. (2001), was used as reference.

Influent

The feeding of both reactors consisted of raw wastewater (Ossemeersen Waste Water Treatment Plant, Ghent, Belgium) containing a total chemical oxygen demand (CODt) concentration of 190 ± 95 mg l^{-1} (Table 2). In order to obtain a medium-strength sewage (around 600 mg COD l^{-1}), the raw wastewater was supplemented with sodium acetate during the experimental period.

GCC and UASB reactor start-up and performance

The anaerobic compartment of the GCC and the UASB reactor were inoculated with 1.6 l and 1.4 l of anaerobic sludge (VSS = 17 g l^{-1}), respectively, coming from an industrial mesophilic anaerobic digester of a potato processing treatment plant (Primeur, Waregem, Belgium).

The reactors were operated at 33 ± 2ºC and two periods can be differentiated: the start-up and the experimental phase. During the start-up (2 months), the most suitable operational conditions for the experimental phase were investigated (Barber and Stuckey, 1999). Increasing organic loading rates (Bv) of 1.8 - 6 g COD l^{-1} d^{-1} and 1.5 - 3.4 g COD l^{-1} d^{-1} were applied in the UASB and the GCC reactor, respectively, in order to determine the maximum capacity of each system (data not shown). From the results obtained, four phases were selected for the experimental period, in terms of Bv, hydraulic retention time (HRT) and the temporary addition of an additive to optimize methanogenesis (Table 3). The additive contained all the necessary vitamins and minerals for a complete and well-balance nutritive balance and it was supplied at a rate of 20 mg l^{-1} reactor d^{-1}. A gravel bed for solids and biomass settling and aeration were included in the aerobic compartment. For aeration, a low energy demand internal filter pump (Eheim aquaball, EH-2208020, Germany), whose function was to rotate concentrically the upper water layers, was used. No sludge was harvested during the reactors performance (solid retention time = ∞).

Analytical methods

CODt and soluble COD (CODs), total suspended solids (TSS), volatile suspended solids (VSS), total Kjeldahl Nitrogen (TKN), total ammonia nitrogen (TAN), total oxidised nitrogen (TON) and pH analysis were routinely

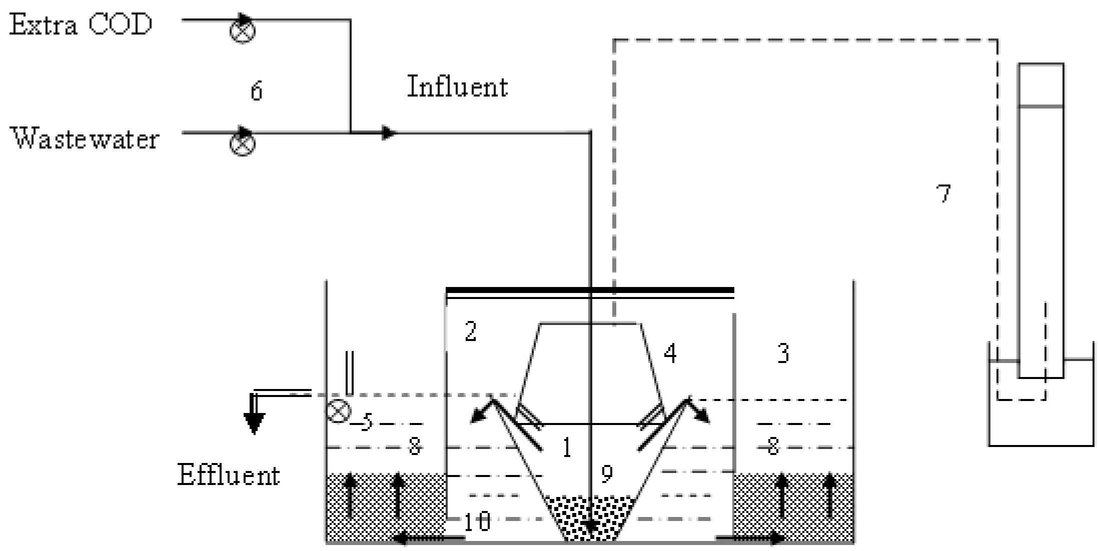

Figure 1. Layout of the lab-scale GCC reactor. 1. Anaerobic compartment. 2. Headspace. 3. Aerobic compartment. 4. Gas deflector. 5. Water cycling pump. 6. Influent pumps. 7. Biogas collection system. 8. Gravel bed. 9. Sludge bed. 10. Anaerobic effluent. (→) Liquid flow. (- - ►) Gas flow.

performed according to Standard Methods (APHA, 2000). Volatile fatty acids content (VFA) was analysed using a gas chromatograph GC 8000 Top Series (CE Instruments, Italy) equipped with an autosampler AS 800 (CE Instruments), a capillary column Phase EC^{TM}-1000 (110-165ºC), a flame ionization detector (FID, 200ºC) and with N_2 as carrier gas. The biogas composition (CH_4 and CO_2) was analysed using a gas chromatograph GC-14B (Shimadzu, Japan) equipped with a custom packed column Alltech PC-5000 (45-80ºC), a thermal conductivity detector (TCD, 200ºC) and with helium as carrier gas.

Economic evaluation of GCC reactor

An estimate was made for the construction costs of a pilot (10 m^3) and an industrial scale (100 m^3) GCC reactor treating sewage at the average production rate typical for rural areas in developing countries of 80 l I.E.$^{-1}$ d^{-1} (Schellinkhout and Collazos, 1992; Van Haandel and Lettinga, 1994). A volume of 10% for the anaerobic compartment of the pilot and industrial scale GCC reactor was selected. An average HRT of 5 hrs (based on the anaerobic compartment) was considered, which provides flow rates of 5 m^3 d^{-1} (serving about 63 I.E.) for the pilot reactor and 50 m^3 d^{-1} (serving about 625 I.E.) for the industrial one. It is expected that the costs of the materials contribute significantly to the overall costs. Therefore, the most and the least expensive materials were considered for the inner compartments, *i.e.* stainless steel and high density polyethylene. Concrete and PVC (not specified) were selected for the outer compartment and pipes, respectively.

Some authors have reported the use of flat thermal solar collectors as an alternative energy to heat anaerobic reactors (Dirk et al. 1999; El-Mashad et al. 2004). The feasibility of a solar-heated GCC reactor was evaluated in the present study with reference values related to a low income country, *i.e.* Ecuador. The flat collectors are supposed to cover 80% of the heating demand, working at 40% efficiency (Thür et al. 2006). In our design, only the anaerobic compartment is heated and it was estimated that 5 hrs of daily light peak are required. Thus, to raise the wastewater temperature from 16ºC (average for Andean regions) to 35ºC, the pilot reactor requires c.a. 22 kWh d^{-1} (29030 MJ y^{-1}), equivalent to 18 m^2 of flat plate collectors (9 plates, 2 m^2 per plate, 0.5 kWh h^{-1} per plate). Each plate is assumed to cost 180 USD (EEQ, 2007). The industrial reactor would require 10 times more energy, *i.e.* 220 kWh d^{-1} or 290, 300 MJ y^{-1} (Goswami et al. 1999), corresponding to c.a. 176 m^2 of flat plate collectors. Heat losses were not taken into account in the aforementioned energy calculations.

RESULTS

CODt removal

A stable feeding solution based on sodium acetate strengthened wastewater was used during the experimental period (Table 2).

Figure 2 shows the variation of the CODt concentrations in the influent and effluent of the GCC and UASB reactors, respectively. The average CODt content of the GCC reactor feeding was 578 ± 53 mg l^{-1}. Low CODt concentrations were detected in the effluent, ranging from 37 to 89 mg l^{-1} (59 ± 13 mg l^{-1}, average concentration). This was also consistent with the low VFA concentrations obtained; only acetate was commonly detected at average concentrations of 3 mg l^{-1}. The CODt removal efficiency in the GCC

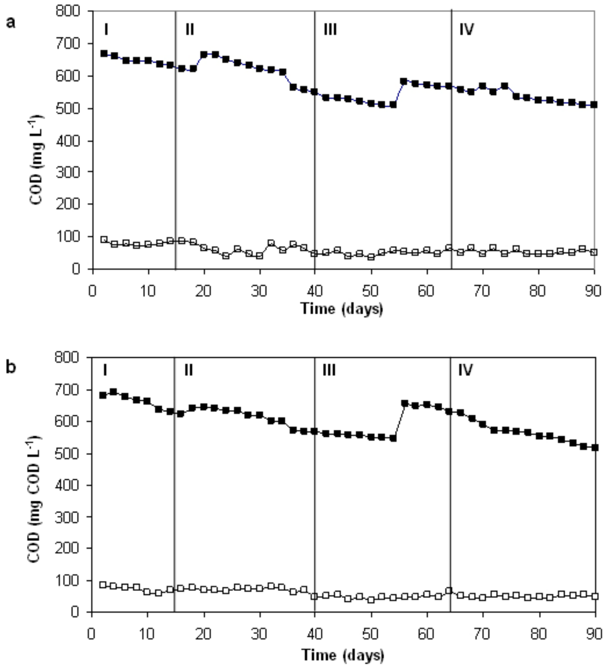

Figure 2. Variation of the CODt in the influent (■) and effluent (□) of the GCC (a) and UASB (b) reactors. See Table 3 for the characteristics of each operational phase.

reactor was 88 ± 1% in phase I, 90 ± 3% in phase II, 91 ± 1% in phase III and 90 ± 1% in phase IV. It resulted in an average removal efficiency of 90 ± 2% for the whole period (Bv = 1.4- 2.2 g COD l^{-1} d^{-1}). It was also noticed that the additive used did not affect the GCC reactor performance in terms of COD elimination.

The CODt influent concentrations of the UASB reactor ranged from 516 to 691 mg l^{-1}, resulting in an average CODt of 600 ± 48 mg l^{-1}, while the levels in the effluent averaged 59 ± 13 mg l^{-1}. As a result, a CODt removal efficiency of 90 ± 2% was attained. Hence, this result was similar to that obtained in the GCC reactor.

Total kjeldahl nitrogen (TKN), total ammonia nitrogen (TAN) and total oxidized nitrogen (TON)

The average TKN value of the feeding was 51 ± 4 mg l^{-1} (Table 2). The GCC and the UASB reactor showed an average TKN removal efficiency of 57 ± 7% and 17 ± 9%, respectively (Table 4). In the GCC reactor, the TKN removal remained constant along the four phases, while the UASB reactor showed increased values. The TAN influent concentrations averaged 37 ± 6 mg l^{-1} (Table 2). Lower TAN concentrations were obtained in the effluent of the GCC reactor (14 ± 4 mg l^{-1}) in comparison with those of the UASB reactor (40 ± 6 mg l^{-1}). Both reactors showed negligible nitrite and nitrate levels in the effluent (< 2 mg l^{-1}), which indicates that the elimination of TKN and TAN in the GCC reactor did not result in the NO_2- and NO_3- production.

Solids analysis

The GCC reactor promoted higher TSS and VSS removal, 40 ± 9% and 86 ± 2%, respectively, than the UASB reactor, 25 ± 6% and 41 ± 15% (data not shown). The reason for this higher solids removal in the GCC reactor could be the deposition of particles in the gravel bed. Indeed the dynamic conditions in the sludge-containing compartment are much lower in the GCC relative to the UASB reactor. Although low solids removal is common in UASB operation, elimination can be improved by optimizing the settling conditions (Mahmoud et al. 2003). No significant biomass growth was observed in any reactor during the experimental period.

Biogas and methane recovery

Figure 3 shows the biogas and methane recovery in the GCC and UASB reactors, respectively, during the experimental period. Biogas and methane production are expressed as volume produced per amount of COD removed. Recoveries refer to the total biogas (or methane) produced in relation to the expected theoretical volumes, 0.5 and 0.35 l of biogas and methane, respectively, per g of COD removed (Tchobanoglous et al. 2003).

The biogas recovery was similar in both reactors, varying from 30 to 60%; however the methane recovery in the GCC reactor (18 - 53%) was lower than that of the UASB reactor (28 - 75%), which could be explained by CH_4 losses in the anaerobic effluent getting into the outer aerobic compartment.

Microbial analysis

A semi-quantitative *fecal coliform* analysis of raw wastewater, using Mc Conckey agar as culture media, showed values of 10^8 - 10^{10} CFU l^{-1} (Table 2). The GCC reactor effluent showed values between $2{\cdot}10^7$ and $4{\cdot}10^7$ CFU l^{-1}, thus indicating a decrease of the fecal bacteria of 1-3 log. Although these concentrations are lower than those reported for UASB reactor effluents (Van Haandel and Lettinga, 1994), *i.e.* 1000 *E. coli*/100 ml, they still exceed the discharge limit proposed by EPA (2004) (< 4.10^2 CFU 100 ml^{-1}).

GCC economics

Table 5 presents the estimated solar flat-plate collectors installation costs. The installation of the proposed flat-plate collectors was priced at 208 and 163 USD m^{-2} for the pilot and the industrial GCC reactors design, respectively. Considering the local price for electricity 0.089 USD kWh^{-1} (without taxes) (EEQ, 2007), the total annual energy costs using a conventional electric resistance equipment would amount to about 894 and 8,932 USD y^{-1}, for the pilot and full scale system, respectively.

Table 6 shows the total estimated costs of the reactors. The item salaries refers to the payment of extra hours required

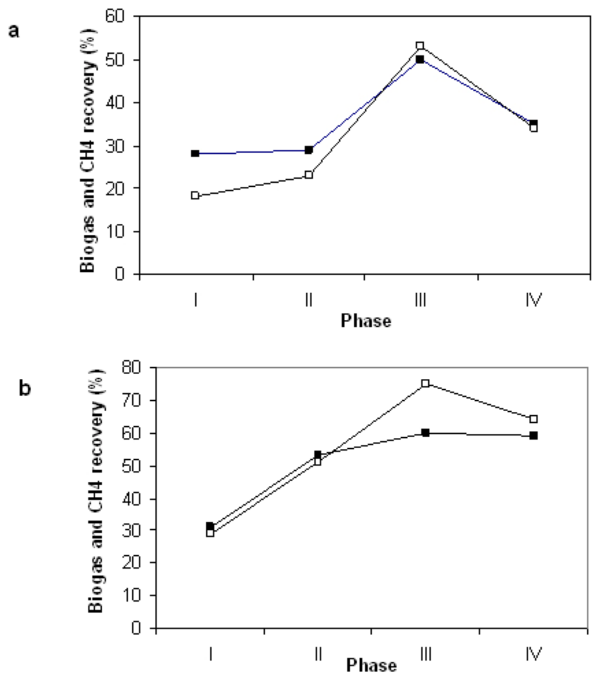

Figure 3. Biogas (■) and methane (□) recovery for the GCC (a) and the UASB (b) reactors.

in case of reactor failure since its control and operation can be performed by the own personnel of the municipal wastewater treatment facilities.

Table 7 shows the annual costs per I.E. and per m^3 of wastewater, respectively. Option 1 at pilot-scale, using plastic material and solar heating, resulted in a total construction cost of 3.9 USD $I.E.^{-1}$ y^{-1}, operational costs of 14.8 USD $I.E.^{-1}$ y^{-1} and 0.6 USD m^{-3} wastewater. From an energetic point of view, 4.7 kWh of electricity per m^3 wastewater were needed. Applying the same conditions to the full-scale system, the results obtained were: total construction costs of 3.0 USD $I.E.^{-1}$ y^{-1}, operational expenditures of 5 USD $I.E.^{-1}$ y^{-1} and 0.3 USD m^{-3} wastewater. In terms of energy, 1.7 kWh of electricity per m^3 wastewater were needed.

DISCUSSION

In this work, a GCC reactor was evaluated technically and economically for sewage treatment in developing countries. A high CODt removal efficiency of 90% can be achieved in the GCC reactor at 33ºC when a medium strength wastewater was treated at Bv of 2.0-2.2 g COD l^{-1} d^{-1} and HRT of 42-45 hrs. The removal of TKN and TAN appears to be also effective, 57 and 61 %, respectively, without increasing nitrite and nitrate concentrations in the effluent. Partial simultaneous nitrification-denitrification process (SND) could occur in the outer compartment (oxic conditions), where increasing dissolved oxygen (DO) concentrations from the lower water layers (gravel bed) to the upper water layers are present (Chelme et al. 2008). Chiu et al. (2007) studied the influence of COD/NH_4^+ ratios on SND process treating domestic wastewater and they stated that a minimum value of 6 for this ratio as well as low DO levels (0.3-0.8 mg l^{-1}) are needed for a partial SND process. Both requirements are likely to happen in the GCC reactor.

Besides, the GCC effluent was odorless and low in turbidity, and a partial hygienisation in terms of fecal bacteria was achieved.

The biogas production in the GCC and UASB systems accounted for 50 and 75% of the theoretical expected value, respectively. The anaerobic treatment of low and medium strength wastewaters usually leads to a loss of more than 50% of biogas in the water phase (Lettinga et al. 1993). In both reactors, the higher biogas and methane recoveries were obtained in phase III. This effect is possibly related to the input of the additive, which optimizes the nutritive balance between the different bacterial groups within the microbial consortium, and thus increasing the methanogenesis.

Table 6 reveals that the type of material (option 1 vs. option 2) and energy are the main factors affecting the construction and operational costs of the GCC system. Although the installation costs of the proposed flat-plate collectors are lower than those reported by Dirk et al. (1999), they double in the best case the reactor construction costs. However, the operational expenditures are lower, saving up to 50% of the electrical needs.

Table 8 shows the costs of different wastewater treatment technologies commonly applied in Latin America. Schellinkhout and Collazos (1992) reported 1,715 USD for the construction of an UASB reactor, serving 96 I.E. (78.4 L sewage $I.E.^{-1}$ d^{-1}) and yielding a total COD removal efficiency of 75%. It resulted in an estimated construction investment of 17 USD $I.E.^{-1}$ and 0.07 USD m^{-3} of wastewater. However, this budget did not take into consideration heating costs (as it was supposed to work at ambient temperature) and overall prices for energy consumption were not reported. In this study, the opex costs obtained for the industrial scale GCC reactor containing polyethylene vessels were 5 USD $I.E.^{-1}$ y^{-1} with solar collectors and 16 USD $I.E.^{-1}$ y^{-1} without solar collectors. Without energy requirements (reactors working at ambient temperature), these costs would decrease to 2 USD $I.E.^{-1}$ y^{-1} and 0.1 USD m^{-3} of wastewater, accordingly. It should be also taken into account that the treatment of a medium strength wastewater (c.a. 500 mg COD l^{-1}) at industrial scale (c.a. 50 m^3 d^{-1}) will generate about 6 m^3 d^{-1} of methane (c.a. 25 kWh d^{-1}), which could cover the remaining 20% of energy not provided by the collectors, and thus decreasing the operation costs of the solar-heated reactor.

Comparing with a European country, such as Belgium (50 m^3 I.E.$^{-1}$ y^{-1}, with an average treatment costs of 30 € I.E.$^{-1}$ y^{-1}), the costs of wastewater treatment in Europe (0.6 € m^{-3} wastewater) double those calculated in this study at large scale (0.3 USD m^{-3} wastewater), but they are of the same order at small scale (0.6 USD m^{-3} wastewater).

Therefore, the simplicity of design, the performance results and the economical analysis indicate that the GCC reactor can be a competitive technology for sewage treatment in developing countries (< 1 USD m^{-3} wastewater).

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APPENDIX
TABLES

Table 1. Dimensions of the lab scale GCC reactor.

	Compartment			
	Inner anaerobic	Outer Anaerobic*	Aerobic	Gas deflector
Diameter (mm)	170-260	300	-	125-200
Height (mm)	205	165	400	185
Length (mm)	-	-	500	-
Width (mm)	-	-	400	-
Volume (l)	7.5	11.6	33.2	5.0

*Volume of anaerobic effluent in the outer compartment is 6.3 l (headspace: 5.3 l).

Table 2. Characteristics of the raw wastewater used to prepare the reactors feeding.

Parameter	Unit	Value
pH		7.6 ± 0.2* (n = 90)
COD_t	mg l^{-1}	589 ± 50* (n = 45)
COD_s	mg l^{-1}	313 ± 25* (n = 20)
NH_4^+-N	mg l^{-1}	37 ± 6 (n = 45)
TON	mg l^{-1}	0 (n = 45)
TKN	mg l^{-1}	51 ± 4 (n = 45)
TSS	mg l^{-1}	213 ± 35 (n = 20)
VSS	mg l^{-1}	128 ± 26 (n = 20)
P-PO_4^{3-}	mg l^{-1}	5 ± 2 (n = 20)
Fecal coliforms	CFU l^{-1}	10^8-10^{10} (n = 20)

*Value after strengthening with sodium acetate.

Table 3. Values of the parameters used in the experimental period.

	Phase I	Phase II	Phase III	Phase IV
	Low rate	High rate	High rate + additive	High rate as in phase II
Duration (d)	Days 1 - 16	Days 17 - 40	Days 41 - 64	Days 65 - 90
Bv (g COD l^{-1} d^{-1})				
GCC[a]	1.4 - 1.6	2.0 - 2.2	2.0 - 2.2	2.0 - 2.2
UASB	1.4 - 1.5	2.0 - 2.5	2.0 - 2.2	2.0 - 2.2
HRT (h)				
GCC	61 - 65[b] 9.7 - 10.4[c]	42 - 45[b] 6.2 - 6.4[c]	42 - 45[b] 6.2 - 6.4[c]	42 - 45[b] 6.2 - 6.4[c]
UASB	10.5 - 11.0	6.5 - 7.0	6.5 - 7.0	6.5 - 7.0
Additive	No	No	Yes	No

[a]Bv value calculated based on anaerobic compartment volume (7.5 l).
[b]HRT based on total reactor volume (47 l).
[c]HRT based on the anaerobic compartment volume.

Table 4. Average values of influent and effluent TKN concentrations (mg Kjeldahl-N l^{-1}) and removal efficiencies (%) in the GCC and UASB reactors.

	Phase	Influent	Effluent	Removal efficiency
GCC	I (n = 8)	45 ± 2	21 ± 3	55 ± 6
	II (n = 12)	51 ± 3	22 ± 4	57 ± 9
	III (n = 12)	55 ± 2	24 ± 2	57 ± 4
	IV (n = 13)	50 ± 3	21 ± 4	57 ± 9
	Average (n = 45)	51 ± 4	22 ± 3	57 ± 7
UASB	I (n = 8)	45 ± 2	40 ± 2	10 ± 4
	II (n = 12)	51 ± 3	45 ± 3	12 ± 4
	III (n = 12)	55 ± 2	47 ± 6	16 ± 9
	IV (n = 13)	50 ± 3	36 ± 3	26 ± 7
	Average (n = 45)	51 ± 4	42 ± 6	17 ± 9

Table 5. Installation costs (in USD) of solar flat-plate collector in the pilot and full-scale GCC reactors (EEQ, 2007).

Item	Pilot reactor (10 m^3)	Industrial reactor (100 m^3)
Collectors array	1,620	15,840
Collectors supporting assemblage	340	2,500
Installation accessories (storage tank, ducts, pipelines)	790	6,500
Stainless steel insulating jacket	270	1,500
Manpower	720[a]	2,400[a]
Total costs	**3,740**	**28,740**

[a]Only for technicians, since the assistants are supposed to be provided by the municipality.

Table 6. Estimated costs (in USD) for the construction, operation and maintenance of the pilot and industrial GCC reactors.

	Pilot reactor (10 m^3)		Industrial reactor (100 m^3)	
	Option 1	Option 2	Option 1	Option 2
Construction				
Anaerobic compartment	130	1,800	1,925	10,300
Headspace compartment	185	2,500	2,900	21,600
Aerobic compartment[a]	700	700	2,900	2,900
Feeding pump	69	69	210	210
Water recirculation pump	69	69	210	210
Accessories (5%)	58	257	407	1,761
Subtotal	**1,211**	**5,395**	**8,552**	**36,981**
Subtotal (per year)[b]	**61**	**270**	**428**	**1,849**
Solar panels installation	3,740	3,740	28,740	28,740
Total	**4,951**	**9,135**	**37,292**	**65,721**
Total (per year)[b]	**248**	**457**	**1,865**	**3,286**
Operational and maintenance costs (per year)				
Energy for pumps[c]	580	580	988	988
Salaries	176	176	352	352
Electricity to cover 20% of anaerobic compartment heating	179	179	1,786	1,786
Subtotal	**935**	**935**	**3,126**	**3,126**
Electricity to cover 80% of anaerobic compartment heating (per year)	715	715	7,146	7,146
Total (per year)	**1,650**	**1,650**	**10,272**	**10,272**
Total costs (per year)				
Using solar collectors	**1,183**	**1,392**	**4,991**	**6,412**
Using electricity	**1,711**	**1,920**	**10,700**	**12,121**

Option 1: Polyethylene vessels with capacity of 1, 2.5, 10 and 15 m^3. Plastigama. National Industry, Ecuador. Option 2: Stainless steel (4 mm); manpower included.
[a]Concrete (Ecuador, local construction prices of 2007, 130 USD/kg concrete).
[b]Considering an operational lifetime of 20 years for reactors and collectors.
[c]0.5 and 0.85 HP for the pilot and industrial reactor, respectively.

Table 7. Yearly costs of GCC reactor per inhabitant equivalent (in USD I.E.$^{-1}$ y^{-1}) and per m^3 of wastewater treated (USD m^{-3} wastewater). See Table 6 for option 1 and option 2 characteristics.

	Pilot reactor (10 m^3)		Industrial reactor (100 m^3)	
	Option 1	Option 2	Option 1	Option 2
Investment costs (USD I.E.$^{-1}$ y^{-1})				
With solar collectors	3.9	7.3	3.0	5.3
Without solar collectors	1.0	4.3	0.7	3.0
Operational and maintenance costs (USD I.E.$^{-1}$ y^{-1})				
With solar collectors	14.8	14.8	5.0	5.0
Without solar collectors	26.2	26.2	16.4	16.4
Total costs (USD I.E.$^{-1}$ y^{-1})				
With solar collectors	18.7	22.1	8.0	10.3
Without solar collectors	27.2	30.5	17.1	19.4
Total costs (USD m^{-3} wastewater)				
With solar collectors	0.6	0.8	0.3	0.3
Without solar collectors	0.9	1.0	0.6	0.7

Table 8. Costs of wastewater treatment technologies applied in Latin America.

Treatment technology	Construction (USD capita^{-1})	O&M[a] (USD capita^{-1} y^{-1})	Reference
GCC[b]			
With solar collectors	60.0	5.0	This study
Without solar collectors	14.0	16.4	This study
PS + AS	84.0	5.2	Sandino, 2007
CEPT + AS	79.0	5.7	Sandino, 2007
CEPT	46.0	4.4	Sandino, 2007
UASB	17.0	2.0	Schellinkhout and Collazos, 1992
Constructed wetlands	16.0	0.6	Arias, 2006
SBR	21.0	2.6	Arias, 2006
Stabilization pond	12.6	0.6	Arias, 2006

[a]O&M: Operational and Maintenance costs. [b]Option 1 (polyethylene vessels) of industrial scale reactor (100 m^3) has been considered for comparison.
GCC: Gradual Concentric Chambers reactor; PS: Primary sedimentation; AS: Activated sludge; CEPT: Chemical Enhanced Primary Treatment; UASB: Upflow Anaerobic Sludge Bed reactor; SBR: Sequential Batch Reactor.