

Technical Problems Ensuing From UASB Reactor Application in Domestic Wastewater Treatment without Pre-Treatment

Sunny Aiyuk^{abc*}, Philip Odonkor^b, Nkoebe Theko^d, Adrianus van Haandel^c and Willy Verstraete^a

Abstract—The performance and stability of a domestic sewage treatment system consisting of an upflow anaerobic sludge blanket (UASB) reactor were assessed. This was to come up with a technical evaluation of using such a system to treat directly such wastewater containing high amounts of suspended solids (SS) in developing countries like Lesotho. Through time, the evolution of the sludge bed was monitored closely, in terms of accumulation of particulate matter and its general quality. The average total chemical oxygen demand (CODt) of the wastewater was 522 mgL⁻¹, and the system could remove 80 % of the organic matter. The sludge production in the reactor system was high (up to 70 % of influent chemical oxygen demand found as suspended solid), necessitating repeated sludge discharges from the reactor, on average every 100 days. Considering the delicate balance of the methanogens in anaerobic reactors, perturbations of the microbiota arose following the sludge extractions, and these promoted reactor imbalance. This further brought about a decrease in reactor performance and hence of the general sustainability of the UASB process when treating domestic sewage directly. In addition, the system could not remove the macronutrients nitrogen and phosphorus. Additional treatment steps would be necessary to remove the suspended solids and nutrients, and thus to effectively treat such a wastewater.

Index Terms—Domestic wastewater, Nutrient removal, Physical entrapment, Rapid sludge build up, UASB

I. INTRODUCTION

Anaerobic digestion has become the most frequently used method for the treatment of medium to high- concentration effluents, due to the economy of the process, and the low generation of surplus sludge. Recently, different anaerobic technologies have also been applied in the treatment of low-concentration wastewaters like domestic sewage, providing good treatment efficiencies at moderate temperatures and low hydraulic retention times (HRTs) [1,2,3,4,5]. Among the various configurations, the upflow anaerobic sludge blanket (UASB) reactor is the most

frequently used reactor in full-scale installations for the anaerobic treatment of domestic wastewaters, being restricted mainly to countries with a warm climate [6].

In the UASB process, the wastewater flows through a granular or flocculent sludge bed [7,8], where different physical and biochemical mechanisms act in order to retain and biodegrade organic substances. Readily biodegradable substances are quickly acidified and then converted into methane and other biogas components, and, with the growth that usually arises, the reactions progress in general according to the empirical Monod equation:

$$\mu = \mu_m \frac{S}{K_S + S} \quad (i)$$

where, μ is the specific growth rate coefficient (h⁻¹), μ_m is the maximum specific growth rate coefficient (h⁻¹), S is concentration of substrate (M/V), and K_S is the half-saturation coefficient, i.e., the substrate concentration at ½ the maximum growth rate.

Substituting the value of μ in the following 1st order equation (because bacteria divide by binary fission):

$$r_g = \mu X \quad (ii)$$

leads one to obtaining an equation for the rate of growth which is:

$$r_g = \frac{\mu_m X S}{K_S + S} \quad (iii)$$

where, r_g is the rate of bacterial growth (M/VT), X is the bacterial concentration (M/V), and the other coefficients are as defined previously.

Actually, as a portion of the substrate is converted to new cells, a portion is oxidized to inorganic and organic end products. These two parameters are related as follows [9]:

$$r_g = -Y r_{su} \quad (iv)$$

where, Y is the maximum yield coefficient (M/M), i.e., ratio of mass of cells formed to mass of substrate consumed, measured during any finite period of logarithmic growth, r_{su} is substrate utilization rate (M/VT), and r_g is as defined previously.

Following, if r_g in equation (iii) is substituted in equation (iv), the rate of substrate utilization can be represented thus:

$$r_{su} = -\frac{\mu_m X S}{Y(K_S + S)} \quad (v)$$

^aLaboratory of Microbial Ecology and Technology (LabMET), Ghent University, Coupure Links 653, B-9000 Ghent, Belgium

^bDept of Environmental Health, National University of Lesotho, P.O. Roma 180, Lesotho

^cResearch Program for Basic Sanitation (PROSAB), Sanitary Engineering Group, Department of Civil Engineering, Federal University of Campina Grande - R Aprigio Veloso 882, 58.109-970 Campina Grande, Brazil

^dMinistry of Health & Social Welfare, Maseru, Lesotho

*Corresponding author. Tel.: +266 59450338

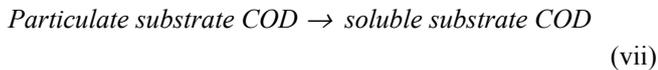
E-mail address: senowater@yahoo.co.uk; seaiyuk@nul.ls, http://nul.ls

where, all terms are defined as previously given. The symbol k , defined as the maximum rate of substrate utilization per unit mass of microorganisms, usually replaces the term $\frac{\mu_m}{Y}$ in equation (v). This enables one to write another important equation:

$$r_{su} = -\frac{kXS}{(Ks + S)} \quad (\text{vi})$$

with all terms as known already.

The hydrolysis and solubilisation of the suspended solids (SS) and macromolecules in the wastewater (also cell lysis) is a slow process which is accomplished by extracellular enzymes excreted by the hydrolytic and acidogenic bacteria [10]. Though often limiting and leading to forms small enough for microorganisms to take up and degrade, there is simply a change in form, with chemical oxygen demand (COD) generally conserved, i.e., no energy is consumed, and so no electrons are removed and no terminal electron acceptor is used [11], leading to a very simple stoichiometry as shown below:



For particulate hydrolysis, in the face of complex situations in which reactions remain ill defined, engineers commonly choose the simplest possible reaction rate expression. They assume that hydrolysis is first order with respect to the particulate substrate [12,13], thus neglecting to a large extent the effect of biomass concentration. A simple expression adopted is based on the work of Stenstrom [11], given as:

$$r_{xs} = -k_h \left[\frac{Xs / Xb, h}{Kx + (Xs / Xb, h)} \right] Xb, h \quad (\text{viii})$$

where, k_h is the hydrolysis coefficient (h^{-1}) (much smaller under anaerobic conditions), Kx is the half-saturation coefficient (mg particulate substrate COD/mg active biomass COD). Also, Xs is the particulate substrate concentration and Xb, h is the active heterotrophic biomass concentration.

This is similar to the Monod equation, except that it is controlled by the particulate substrate to biomass ratio, rather than by the particulate substrate concentration. This is necessary because the reaction is thought to be surface mediated, and thus depends on the presence of extracellular enzymes whose quantity is proportional to the biomass concentration.

In batch systems (substrate, final products and biomass concentrations), the following sigmoid curve model was proposed [14] to describe the main process parameters for the decay of solids (particulate matter), as shown in equation (ix) below:

$$x_t = x_{\max} \sum_i \frac{1}{(i-1)!} \left(\frac{t-t_c}{bs} \right)^{i-1} \text{Exp} \left(-\frac{t-t_c}{bs} \right)$$

with i varying from 1 to $n+1$, and,

where, $n+1$ is the curve order, x_{\max} is maximum

concentration of x , bs is a time constant, t is time and t_c is a translation along the x -axis.

Accurate anaerobic process modelling can be vital not only to design anaerobic digesters, but also to have a deep insight into the biochemical processes occurring [15]. Since the hydrolysis of particulate matter progresses only very slowly, during the treatment, complex substrates could leave the digester largely unaltered [16,17,18]. In UASB systems, nevertheless, the sludge bed can act as a filter to the SS, thereby increasing their specific residence time. In this way, the UASB reactor may achieve high COD and SS removals at relatively short hydraulic retention times (HRTs). However, the accumulation of SS in the sludge bed can provoke the displacement and dilution of active cells, the so-called biocatalysts [19], and leading to the formation of a sludge with a low methanogenic activity, a drawback which can be intensified by the accumulation of toxic or inhibitory substances present in domestic wastewater. Such accumulation must also call for frequent withdrawal of excess sludge to avoid massive washout [20,21].

The aim of this research was to employ a lab-scale UASB reactor to investigate technically the treatment of municipal (domestic) wastewater (sewage) in the light of effluent discharge, reuse and/or recycling, under warm conditions. Attention was paid to the accumulation of active and inactive biomass in the digester, i.e. the performance and sustainability of the treatment were evaluated.

II. MATERIALS AND METHODS

A. Domestic Wastewater

Previously screened and dewatered domestic wastewater was collected from the Ossemeersen wastewater treatment plant, city of Ghent (Belgium). The wastewater was collected from the treatment station every other week, and was stored at 4°C in tightly closed, 40-50 L containers.

The wastewater was pumped just below the water surface, using a submersible pump (Nocchi VIPVORT 130/5, Lugnano (Pisa), Italy). The collection went on for a period of 15 months, what constituted also the experimental period.

B. Experimental

The wastewater was pumped semi-continuously from an influent tank into the UASB reactor. The tank content was not mixed to avoid introduction of air. The gas-tight, glass UASB reactor (Schott-Duran, Mainz, Germany) was operated at $33 \pm 1^\circ\text{C}$. It was seeded with 250 mL of granular anaerobic sludge obtained from a potato processing wastewater treatment plant (Primeur, Waregem, Belgium) with a specific methanogenic activity (SMA) of $0.40 \text{ g CH}_4\text{.COD g}^{-1} \text{ VSS}^{-1}\text{d}^{-1}$. The reactor operating parameters are given in Table I.

The UASB reactor technical details have been previously given [22]. The influent pump was operated every hour for 5 min and supplied $5.0 \pm 0.4 \text{ L}$ (phase 1) or $7.5 \pm 0.5 \text{ L}$ (phase 2) of influent each day.

TABLE I. OPERATING PARAMETERS OF THE UASB REACTOR.

Parameter	Value (\pm Standard deviation)
Temperature ($^{\circ}\text{C}$)	33 (1)
Reactor liquid-filled volume (L)	2.10 (0.01)
Feeding rate (L d^{-1})	5.0, then 7.5 (0.5)
Vol. loading rate (B_v) ($\text{g COD L}^{-1} \text{d}^{-1}$)	1.3, later 2.5
Hydraulic retention time (HRT) (h)	10.0 (0.2), then 6.7 (0.2)
Upflow velocity (V_{up}) (m h^{-1})	1.0 (0.1)
Influent COD : N : P ratio	65:5:1
Inoculum sludge volume (mL)	250
Initial specific methanogenic activity of sludge ($\text{g CH}_4\text{-COD/g VSS.d}$)	0.40

The volumetric loading rate (B_v) was on average 1.3 g COD $\text{L}^{-1}\text{d}^{-1}$ during phase 1 (range of 0.4 – 3.0 g COD $\text{L}^{-1}\text{d}^{-1}$) and 2.5 g COD $\text{L}^{-1}\text{d}^{-1}$ during phase 2 (range of 1.0 – 4.3 g COD $\text{L}^{-1}\text{d}^{-1}$), corresponding to hydraulic retention times (HRTs) of 10 ± 0.2 h and 6.7 ± 0.2 h, respectively. The COD removal efficiency of the UASB reactor was calculated every other day. At the end of a two-day period, the influent remaining in the influent container, which was more concentrated than the influent used during the beginning of the cycle due to settling of SS, was well mixed, sampled, and the total chemical oxygen demand (COD_t) was analyzed. Using this measurement, combined with the COD_t present in the influent container at the beginning of the cycle, the amount of COD_t received by the reactor over a two-day time period was calculated. Using this value combined with the total amount of COD_t that left with the reactor effluent during the two-day time period allowed calculation of the COD_t removal efficiency. This approach of calculating the COD_t removal efficiency was chosen rather than the usual approach of computing reactor efficiency directly from influent and effluent COD concentrations, what would tend to overestimate efficiency when treating a wastewater as domestic sewage that has a high fraction of suspended matter.

C. Analytical Techniques

The pH was measured with a digital pH-meter (Knick-Elcolab n.v., Kruikebe, Belgium). Alkalinity was determined by acid titration from the initial pH of the samples to pH 4.5. Methane (CH_4) and carbon dioxide (CO_2) in the biogas of the UASB reactor were analyzed with an Intersmat IGC 120 MB gas chromatograph (Intersmat, Lyon, France) connected to a Hewlett-Packard 3390 A integrator. Volatile fatty acids (VFA) in the effluent of the UASB reactor were extracted by diethylether as described [23], and measured with a gas chromatograph (Carlo Erba Fractovap 4160, Milano, Italy) equipped with a flame-ionization detector (FID) and a Delsi-Nermag integrator (ENICA-31). The gas chromatograph was equipped with a capillary free fatty acid phase column (25 m by 0.53 mm; 1.2 μm film thickness). The carrier gas was nitrogen at a flow rate of 20 mL min^{-1} . Temperatures were 130 $^{\circ}\text{C}$ (column) and 195 $^{\circ}\text{C}$ (injection port and FID). For total Kjeldahl nitrogen (TKN) determination, a sample was digested according to the Kjeldahl procedure. NH_3 was distilled off by a Kjeltetec

apparatus (Tecator 2200 Kjeltetec Auto Distillation, S-263 21, Hogamas, Sweden), captured by a boric acid solution, and the concentration was determined by titration with sulphuric acid [24]. For total ammoniacal nitrogen (TAN) (i.e., $\text{NH}_4\text{-N} + \text{NH}_3\text{-N}$), the TKN procedure was used, but the digestion step was omitted. Total phosphorus (P_{tot}) was determined by ashing at 450 $^{\circ}\text{C}$, dissolution in nitric acid, and colorimetric analysis at a wavelength of 700 nm [24]. For orthophosphate ($\text{PO}_4\text{-P}$) analysis, the digestion step was omitted.

Biochemical oxygen demand (BOD) was determined by the Oxytop method [24]: samples to which an inoculum, buffer, nutrients, and a nitrification inhibitor were added were incubated for 5 days at 20 $^{\circ}\text{C}$ in partially-filled bottles fitted with electronic stoppers from which results were directly read. Final results were obtained by using a suitable dilution factor. Other parameters (% solids, total suspended solids (TSS), volatile suspended solids (VSS), COD_t , soluble chemical oxygen demand (CODs)) were determined by their respective standard methods [24]. Analyses of COD_t were performed twice weekly, the pH was analyzed every other day, and the other parameters were analyzed once every two weeks.

The SMA was analyzed in triplicate as previously described [25]. The SMA test was carried out by the pressure-bottle technique, using acetate as the substrate in an anaerobic medium. Activity was determined as the maximum slope of the graph of methane formation (g $\text{CH}_4\text{-COD}$) per g of VSS against time [26].

III. RESULTS

A. Wastewater Characteristics

Average wastewater characteristics with standard deviations (SDs) for the 450-day operational period are shown in Table II. The average COD_t was 522 mgL^{-1} , the COD/N/P ratio was about 65/5/1, and the TSS and VSS were respectively 200 mgL^{-1} and 125 mgL^{-1} , implying that this wastewater was a low-strength domestic wastewater [27].

Approximately 70% of the COD_t was present as suspended material. This value falls between values obtained for the same region in Belgium [28]. The COD_t/VSS ratio was on average 1.3 and the TSS/ COD_t ratio was 0.4. There were large variations in the COD_t concentration of the raw wastewater (200 to 1,250 mgL^{-1}), in agreement with seasonal variations in domestic wastewater composition [29]. The average amount of P_{tot} in the raw wastewater was 8 ± 3 mg/L . The TKN was 39 ± 9 mgL^{-1} . From the COD/N/P ratio of 65/5/1, the N and P concentrations relative to the COD content in the wastewater were higher than the minimum nutrient requirements necessary for anaerobic digestion (COD/N/P ratio of 400/5/1) [30]. In this regard, therefore, treatment in a UASB reactor should be feasible.

TABLE II. COMPOSITION OF THE RAW DOMESTIC SEWAGE.

Parameter (mg L ⁻¹)*	Average (± STD)
TSS	200 (15)
VSS	125 (21)
COD _t	522 (300)
COD _s	154 (112)
BOD ₅	208 (213)
TKN	39 (9)
NH ₄ ⁺ -N	24 (11)
P _{tot}	8 (3)
PO ₄ -P	4 (2)
pH	7.4 (0.1)
Alkalinity (mg CaCO ₃ L ⁻¹)	300 (37)

*pH without unit

B. UASB Reactor Performance

The COD_t variations in the UASB reactor influent and effluent are shown in Fig. 1. The average COD_t and COD_s concentrations of the UASB influent were 522 ± 300 mgL⁻¹ and 154 ± 112 mgL⁻¹, respectively. Average effluent COD_t and COD_s concentrations were 98 ± 56 mgL⁻¹ and 67 ± 9 mgL⁻¹, respectively. Fig. 2 shows the reactor efficiency for COD removal over time. The figure also highlights periods when the reactor performance fell to unacceptable levels, and so excess sludge was removed from the reactor sludge bed. The COD_t removal efficiency averaged 65 ± 15 %, for a volumetric loading rate (Bv) of 1.8 ± 0.7.

C. Sludge Bed Height And Sludge Characteristics

The height of the sludge bed increased progressively, from 13 cm (255 cm³ of reactor volume) on day 1 to 44 cm (864 cm³) on day 106 (Fig. 3). By this time the reactor efficiency had dropped from close to 80 % to 38 %, and the sludge bed height was then decreased to 15 cm (295 cm³). This thus necessitated the removal of 569 cm³ of excess sludge (565 g). Actually, it was necessary to decrease the sludge bed height four times during the entire operational period of about 450 days, as shown also in Fig. 3.

The behaviour of the sludge bed in the reactor was analyzed by taking sludge samples from different levels. The results of the operations involving the removal of excess sludge from the reactor are presented in Table 3. The methanogenic activity of the sludge decreased from 0.4 g CH₄-COD g⁻¹VSS-1d-1 for the inoculum to 0.27 g CH₄-COD g⁻¹VSS-1d-1 after 85 d of operation. Correlating these results with data from Table III, it was observed that the accumulated organic matter at the upper zone of the UASB was significant, but was not converted to methane, as the methanogenic activity of VSS in this zone was very low or zero.

Therefore, recirculation or external digestion of the accumulated organics in the upper zone of the UASB was

thought to be necessary in order to achieve complete anaerobic stabilisation of the wastewater components.

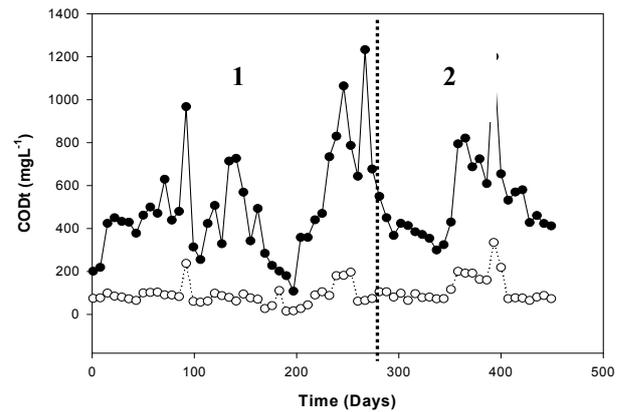


Fig. 1. Influent (●) and effluent (○) COD concentrations of UASB reactor over the entire study period (1 & 2 indicate operational phases)

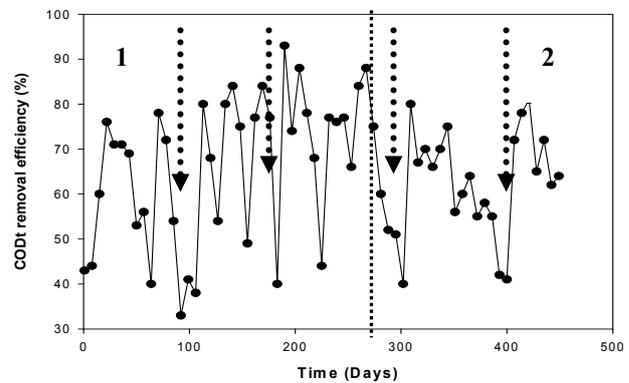


Fig. 2. COD_t removal efficiency over time (thick arrows show periods when excess sludge was removed from the reactor, and 1 & 2 indicate phases)

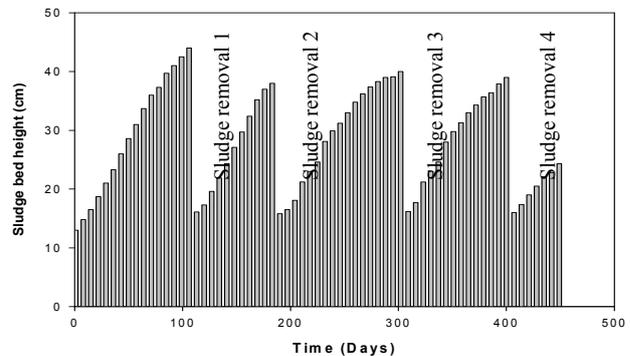


Fig. 3. Evolution of the bed height of the experimental reactor

TABLE III. SEQUENCE OF REACTOR SLUDGE REMOVALS DURING TEST PERIOD

Time (Days)	Bed height (cm)	Sludge vol. in reactor (cm ³)	Reactor efficiency (%)	New height of bed (cm)	Excess sludge removed (cm ³)
1	13	255	NA	NA	NA
106	44	864 ^a	38	15	569
183	38	746 ^a	40	15	451

302	40	785*	40	15	490
400	39	766*	41	15	471

NA implies not applicable

*Approximate volumes as were calculated from sludge bed heights

D. Nutrient Balances

The macronutrients nitrogen (N) and phosphorus (P) were not decreased in concentration by the anaerobic treatment. While total nitrogen (TKN) levels tended to decrease in the effluent, there was generally an increase in ammonium. The influent TKN ranged from 22-63 mgL⁻¹, with an average (\pm STD) concentration of 39 ± 9 mgL⁻¹. Effluent TKN ranged from 9-37 mgL⁻¹, with a mean (\pm STD) of 20 ± 8 mgL⁻¹. The removal efficiency of the TKN was in the range 17-72 %, with an average (\pm STD) of 48 ± 1 %. Ammonium nitrogen variations were in the range 6-50 and 5-59 mgL⁻¹, with mean values (\pm STD) of 24 ± 9 and 27 ± 10 mgL⁻¹, for the reactor influent and effluent, respectively. Effluent ammonium concentration was most often higher than the influent concentration. Total P and soluble orthophosphate (PO₄³⁻⁻P) concentrations of the reactor influent were 8 ± 3 and 4 ± 2 mgL⁻¹, respectively. The effluent concentrations were generally the same as the influent concentrations.

E. Biogas And Methane Recoveries

Fig. 4 shows time courses for total biogas and methane production. Biogas production here refers to the total biogas recovered, in relation to the theoretical amount expected theoretically (0.5 Lg⁻¹ COD removed), and methane production refers to the relative abundance of methane in the biogas. This is the biogas and methane actually recovered, in addition to that, which escaped, in dissolved form, in the effluent.

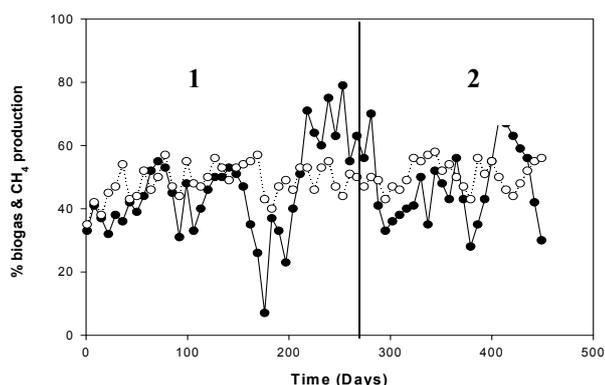


Fig. 4. Plots of biogas produced in reactor (●) and methane concentration (% measured in biogas) (○) over the experimental period (bold numbers indicate the operational phases)

Actually, the produced biogas ratios deviated reasonably from the theoretical expectation, and ranged from 7 to 79 %. From Fig. 4, the biogas content in methane was generally low, ranging from 35-57 %, but showed a slight tendency to increase with time, probably in consonance with a maturation of the reactor biomass. This could especially be so from the fact that the pH remained all through within an optimal range of 6.8-7.5, and no substantial recording of VFAs was made.

IV. DISCUSSION

The particulate suspended matter content of the influent wastewater was rather high, amounting to up to 70 % of the total COD. The hydrolysis and further anaerobic conversion of such complex particles require a much longer residence time than that used in this study [31]. This thus led to their accumulation in/on the sludge bed, and thus the sludge bed height increased rapidly over time [8]. Similar observations were reported [32,33], where the removal of SS by UASB reactors treating domestic sewage in the mesophilic temperature range was mainly by the physical process of solid retention in the sludge bed. In this way the SS and CODt removals can surpass 70 % [32]. It was also reported that when using the UASB to treat raw domestic sewage, an important fraction of excess sludge arises from interception in the sludge bed of poorly biodegradable solids found in the influent [34]. This means that it would be desirable to uncouple the two phases for separate treatments [35]- the liquid phase with soluble organic matter, and the solid obdurate phase. This is especially the case when the UASB process becomes the main option [19], calling thus for a pre-treatment to free the liquid phase of the solids.

The reactor performance in terms of organic matter removal remained usually high throughout the experimental period, save the periods when the sludge bed height had become too high and there was massive washout (see Figures 2 and 3). At this time excess sludge was removed from the reactor sludge bed to lower the height, and so restore the efficiency. The removal of the particles as such during the sludge removals, together with the excessive sludge accumulation, caused a deterioration of sludge quality, expressed as a drop in SMA over time [36]. The SMA dropped from $0.4 \text{ g CH}_4\text{-COD g}^{-1}\text{VS}^{-1}\text{d}^{-1}$ for the inoculum sludge to $0.27 \text{ g CH}_4\text{-COD g}^{-1}\text{VS}^{-1}\text{d}^{-1}$ (from bottom of sludge bed) for the final sludge. However, the final SMA value was still higher than $0.1 \text{ g CH}_4\text{-COD g}^{-1}\text{d}^{-1}$ [2], $0.14\text{-}0.17 \text{ g CH}_4\text{-COD g}^{-1}\text{d}^{-1}$ [32], $0.6\text{-}0.2 \text{ g CH}_4\text{-COD g}^{-1}\text{d}^{-1}$ [37] reported for UASB biomass treating raw domestic sewage. The total active biomass content probably decreased progressively, and stabilized at the end of the operational period (8 g VSS L^{-1} for the inoculum sludge down to 0.7 g VSS L^{-1} at the end of the study). Therefore, the low amount of active biomass contained in the UASB digester could be one restrictive factor that needed to be resolved to enhance the reactor efficiency.

The SMA value approached zero towards the top of the sludge bed, indicating that the top part was mostly comprised of inactive solids. This could partially be possible from the fact that during reactor feeding coupled to the recycle flow, the sludge bed particles are practically buoyed, and on descent when the current wanes (shutting of feeding pump), the smaller influent particulate matter settles last, leading to an upward fining of the sludge bed, reminiscent of many natural stratigraphic patterns [38]. The particles also surround the active biomass, and this can lead to substrate transfer limitation [22]. Such plentiful occurrence of particulate matter in domestic wastewater can also lead to biogas of poor quality, usually with low amounts of recoverable methane [2]. The mean methane recovery (\pm

STD) in this study was $49 \pm 5\%$. The amount recovered was so small that there would be no reason for harnessing it.

The rapid increase in the sludge bed height with time meant that a large amount of the organic particulate matter was mainly entrapped by interception [34,39,40], causing the UASB reactor to have mainly acted in this case as a kind of physical filter. This thought receives added support from the fact that the biogas recovery was low, on average 46%. Even, the repeated removal and handling of excess reactor sludge from large-scale anaerobic digesters would call for enhanced operational costs, apart from inactive solids occupying the space of the biocatalysts [19]. To put all these inherent drawbacks in context, it seems worthwhile at this point to quote [6], who noted as follows: "For the treatment of partially soluble complex wastewater the required removal efficiency of the SS should be given special attention". It is contended that in conventional UASB treating raw domestic wastewater, excess sludge discharge has to be done about weekly, in order to control the sludge hold up effect on the effluent quality [2].

From the trends observed, the performance behaviour of the UASB reactor never became stable through time, and there was a generally erratic behaviour, leading to large variations in performance. The initiation of phase 2 caused reactor instability that brought a progressive drop in reactor performance, but the reactor picked up in the later part of the phase, keeping still its generally wavy pattern.

The efficiency of single UASB digesters treating domestic wastewaters is reported to be in the range 50 to 75% for COD removal and 70 to 80% for SS removal at a typical HRT between 5 and 10 h [2,41,33]. Our results thus agree with previously published findings. Many previous works did not report actively on those problems that could arise from the presence of plentiful suspended solids, e.g., the decrease in SMA, due to the occupation of reactor space by inactive solids, and the perturbations caused on the reactor microbiota.

Looking at the small amount of biogas that was recovered during the study, this was not unexpected, as a longer residence time was required for the particulate COD that accumulated in the reactor sludge bed to be digested, needing thus an uncoupling of the HRT from the solid retention time (SRT). It may thus be much better to eliminate the particulate COD for separate treatment in a continuously stirred tank reactor (CSTR), and the liquid portion fed into the UASB. As a whole, however, only small amounts of biogas are obtainable from sewage treatment, as the influent COD concentrations remain quite low. This makes sewage treatment not important for energy recovery. The biogas recovery may thus be of no real economic importance, implying that anaerobic treatment of low strength wastewater cannot be used as an energy recovery process and that this important benefit of anaerobic treatment in general could not be achieved in the present application [42].

The low amounts of VFAs recorded both for the influent and effluent go in line with some views [43,44], enunciating that VFAs are generally low in domestic sewage systems. The system, like other anaerobic processes, failed to decrease the nutrient released with the effluent, needing thus an

optimization to guarantee better environmental protection. The effluent COD was also usually high, necessitating thus a post-treatment to ensure efficient reuse and/or recycling.

V. CONCLUSION

The application of the UASB process for the direct treatment of domestic sewage was effective in producing effluents with somewhat low amounts of organic matter, but not sufficient for efficient recycling/reuse. There were serious limitations inherent within the system: inefficiency in removing nutrients, and difficulties in removing suspended solids, leading to rapid rise in sludge bed height and frequent sludge removal. The high rate of sludge production, due to the accumulation of SS, was certainly a disadvantage, as sludge handling in full-scale installations can be expensive. Apart from the high cost, the removal would undoubtedly cause inactive solids to occupy reactor space, and would increase the disturbance imposed on the reactor microbiota, especially on the slow-growing methanogens.

Since the UASB application is low-cost and effective in removing organic matter, especially in the dissolved state, a coupling with other low-cost processes to handle effectively the suspended solids, nutrients and a large fraction of the pathogens would appear to be promising. The resulting system would as such respond to direct environmental concerns, and, from the low investment and operational costs, would be amenable to use in developing countries as Lesotho.

ACKNOWLEDGMENT

This research was sponsored by a grant from the Ghent University, Belgium. Fruitful interactions with Joris Roels and Nollet Hendrick are acknowledged.

REFERENCES

- [1] G. Lettinga, A. F. M. Van Velsen, S. W. Homba, W. de Zeew and A. Klapwijk, Use of the upflow sludge blanket (USB) concept for biological wastewater treatment, specially for anaerobic treatment, *Biotech. Bioeng.* Vol. 22, pp. 699-734 (1980).
- [2] G. Lettinga, A. W. A. de Man, A. R. M. Van der Last, W. Wiegant, K. Knippenberg, J. Frijns and J.C.L. Van Buuren, Anaerobic treatment of domestic sewage and wastewater, *Water Sci. Technol.* Vol. 27, pp. 67-73 (1993).
- [3] S. M. M. Vieira and M.E. Souza, Development of technology for the use of the UASB reactor in domestic sewage treatment, *Water Sci. Technol.* Vol. 18, pp. 109-121 (1986).
- [4] A.R.M. Van der Last and G. Lettinga, Anaerobic treatment of domestic sewage under moderate climate (dutch) conditions using upflow reactors at increased superficial velocities, *Water Sci. Technol.* Vol. 25, pp. 167-178 (1992).
- [5] A. Schelinkhout, UASB technology for sewage treatment: experience with a full scale plant and its applicability in Egypt, *Water Sci. Technol.* Vol. 27, pp. 173-180 (1993).
- [6] G. Lettinga and L. W. Hulshoff Pol UASB process design for various types of wastewaters, *Water Sci. Technol.* Vol. 24, pp. 87-107 (1991).
- [7] I. Ruiz, M. Soto, M. C. Veiga, P. Ligeró, A. Vega and R. Blázquez, Performance of and biomass characterization in a UASB reactor treating domestic waste water at ambient temperature, *Water SA* Vol. 24, pp. 215-222 (1998).
- [8] S. E. Aiyuk, I. Forrez, L. De Kempeneer, A. van Haandel and W. Verstraete, Anaerobic and complementary treatment of domestic sewage in regions with hot climates - A review. *Biores. Technol.* Vol. 97 (17), pp. 2225-2241 (2006).
- [9] R. Crites and G. Tchobanoglous, *Small and decentralized wastewater management systems.* Mc-Graw Hill, Boston, USA (1998).

- [10] W. Gujer and A. J. B. Zehnder, Conversion processes in anaerobic digestion, *Water Sci. Technol.* Vol. 15, pp.127-167 (1983).
- [11] C. P. L. Grady Jr., G. T. Daigger and H. C. Lin, *Biological wastewater treatment* (2nd Ed.). Marcel Dekker, New York, USA (1999).
- [12] W. Gujer, The effect of particulate organic material on activated sludge yield and oxygen requirement, *Prog. Water Technol.* Vol 12, pp. 79-95 (1980).
- [13] J. D. Bryers and C. A. Mason, Biopolymer particulate turnover in biological waste treatment systems: a review, *Bioprocess Eng.* Vol. 2, pp. 95-109 (1987).
- [14] A. Valentini, G. Garut and A. Rozzi, Analisi delle cinetiche di degradazione anaerobica del particulate organico e difinizione di un nuovo approccio allo studio, *IA Ingegneria Ambientale, XXV ½*, pp. 44-52 (In Italian) (1996).
- [15] A. Valentini, G. Grant and A. Rozzi, Anaerobic degradation kinetics of particulate organic matter: a new approach, *Water Sci. Technol.* Vol. 36, pp. 239-246 (1997).
- [16] M. Halalsheh, Z. Sawajneh, M. Zubi, G. Zeeman, J. Lier, M. Fayyad and G. Lettinga, Treatment of strong domestic sewage in a 96 m³ UASB reactor operated at ambient temperatures: two-stage versus single-stage reactor, *Biores. Technol.* Vol. 96, pp. 577-585 (2005).
- [17] S. Uemura, H. Harada, A. Ohashi and S. Torimura, Treatment of wastewater containing large amount of suspended solids by a novel multi-staged UASB reactor, *Environ. Technol.* Vol. 26, pp. 1335-1362 (2005).
- [18] L. L. Zhang, B. Zhang, Y. F. Huang and W. M. Cai, Application of aerobic granular sludge in polishing the UASB effluent. *Environ. Technol.* Vol. 26, pp. 1327-1334 (2005).
- [19] W. Verstraete, T. Tanghe, A. De Smul and H. Grootaerd, "Anaerobic biotechnology for sustainable waste treatment", in *Biotechnology in the sustainable environment*, Sayler (ed.), Plenum Press, New York, USA, pp. 343-359 (1997).
- [20] P. F. F. Cavalcanti, E. J. S. Medeiros, J. K. M. Silva and A. Van Haandel, Excess sludge discharge frequency for UASB reactors. *Water Sci. Technol.* Vol. 40, pp. 211-219 (1999).
- [21] P. F. F. Cavalcanti, Integrated application of the UASB reactor and ponds for domestic sewage treatment in tropical regions, Ph.D Thesis, Wageningen University, The Netherlands (2003).
- [22] S. E. Aiyuk and W. Verstraete, Sedimentological evolution in an UASB treating SYNTHES, a new representative synthetic sewage, at low loading rates, *Biores. Technol.* Vol. 93, pp. 269-278 (2004).
- [23] L. V. Holdeman, E. P. Cato and W. E. C. Moore, *Anaerobic laboratory manual*, Virginia polytechnic institute and state university, Blacksberg, Virginia, USA (1977).
- [24] APHA, *Standard Methods for the Examination of Water and Wastewater*, 18th ed., American Public Health Association (APHA)/American Water Works Association (AWWA)/Water Environment Federation (WEF), Washington DC, USA (1992).
- [25] D. Valcke and W. Verstraete, A practical method to estimate the acetoclastic methanogenic biomass in anaerobic sludge, *J. WPCF* Vol. 52, pp. 720-729 (1983).
- [26] J. Thaveesri, D. Daffonchio, B. Liessens, P. Vandermeren and W. Verstraete, Granulation and sludge bed stability in upflow anaerobic sludge bed reactors in relation to surface thermodynamics. *Appl. Environ. Microbiol.* Vol. 61 (10), pp. 3681-3686 (1995).
- [27] G. Tchobanoglous and F. L. Burton, *Wastewater engineering: treatment, disposal and reuse* (3rd Ed.), McGraw-Hill, Inc., New York, USA (1991).
- [28] L. Kuai, W. Kerstens and W. Verstraete, Low-cost and small-scale sewage treatment system. 5th FAO/SREN workshop on anaerobic conversions for environmental protection, sanitation and re-use of residues, Ghent, Belgium (1997).
- [29] M. Lansdell, Fifteen years of practical sewage treatment in Venezuela, *Water Sci. Technol.* Vol. 33, pp. 39-46 (1996).
- [30] J. Thaveesri, Granulation and stability in upflow anaerobic sludge bed reactors in relation to substrates and liquid surface tension, Ph.D Thesis, Ghent University, Belgium (1995).
- [31] A. G. Rao, G. V. Naidu, K. K. Prasad, N. C. Rao, S. V. Mohan, A. Jetty and P. N. Sarma, Anaerobic treatment of wastewater with high suspended solids from a bulk drug industry using fixed film reactor (AFFR), *Biores. Technol.* Vol 96, pp. 87-93 (2005).
- [32] A. Barbosa and G. L. Sant'Anna Jr., Treatment of raw domestic sewage in an UASB reactor. *Water Res.* Vol. 23, pp. 1483-1490 (1989).
- [33] K. Wang, Integrated anaerobic and aerobic treatment of sewage, Ph.D Thesis, Wageningen University, Wageningen, The Netherlands (1994).
- [34] A. C. Van Haandel and G. Lettinga, *Anaerobic sewage treatment: a practical guide for regions with a hot climate*, John-Wiley and sons, New York, USA (1994).
- [35] E. Sanchez, R. Borja, L. Travieso, A. Martin and M. F. Colmenarejo, Effect of organic loading rate on the stability, operational parameters and performance of a secondary upflow anaerobic sludge bed reactor treating piggery waste, *Biores. Technol.* Vol. 96, pp. 335-344 (2005).
- [36] N. J. A. Mahmoud, Anaerobic pre-treatment of sewage under low temperature (15°C) conditions in an integrated UASB-Digester system, Ph.D Thesis, Wageningen University, Wageningen, The Netherlands (2002).
- [37] H. Draaijer, J. A. W. Maas, J. E. Shaapman and A. Khan, Performance of the 5 MLD UASB reactor for sewage treatment at Kampur, India. *Water Sci. Technol.* Vol. 25, pp. 123-133 (1992).
- [38] S. E. Aiyuk and W. Verstraete, Sedimentological evolution in an UASB treating low-strength wastewater. Belgian committee of the Int. Water Association (B-IWA) workshop, 18th March 2002. Poster presentation (2002).
- [39] Y. Kalogo, Reactor start-up and process design for the anaerobic treatment of domestic wastewater, Ph.D Thesis, Ghent University, Belgium (2001).
- [40] J. Amoako, Anaerobic treatment of raw, pre-treated and synthetic municipal wastewater using UASB technology, M.Sc. Thesis, Ghent University, Belgium (2002).
- [41] M. T. Kato, J. A. Field and G. Lettinga, The anaerobic treatment of low strength wastewaters in UASB and EGSB reactors, *Water Sci. Technol.* Vol. 36, pp. 375-382 (1997).
- [42] S. Uemura and H. Harada, Treatment of sewage by a UASB reactor under moderate to low temperature conditions, *Biores. Technol.* Vol. 72, pp. 275-282 (2000).
- [43] K. Mergaert, B. Vanderhagen and W. Verstraete, Applicability and trends of anaerobic pre-treatment of municipal wastewater, *Water Res.* Vol. 26, pp. 1025-1033 (1992).
- [44] S. E. Aiyuk, Development of a sustainable treatment technology for domestic sewage, Ph.D. Thesis, Ghent University, Belgium (2004).