Application of an innovative methodology to improve the starting-up of UASB reactors treating domestic sewage

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Abstract This study shows the results obtained during the starting-up evaluation of an UASB reactor treating domestic sewage. It is located in the municipality of Ginebra, Valle del Cauca region in Colombia. Its design flow is 7.5 l/s with a maximum capacity of 10 l/s. The reactor was seeded with a deficient quality inoculum which accounted for 20% of the total reactor volume. The starting-up methodology comprised the sequential washing of the sludge (inoculum) by applying three different upflow velocities. This procedure resembles what other authors term the "selective pressure method". Once the sludge was washed, the reactor was started-up with an initial hydraulic retention time (HRT) of 24.9 hours, which was steadily reduced down to 6.7 hours in the final stage. Along the starting-up phase, there was a positive evolution in terms of quantity, quality and spatial distribution of the sludge. Consequently, there was a positive evolution in organic matter removal mechanisms. For HRT above 14 hours, the removal mechanisms were mainly physical whilst for HRT below 9 hours the removal mechanisms were mostly biological. Based on the above considerations and on the water quality parameters measured, it may be concluded that the start-up of an UASB reactor for domestic sewage treatment seeded with a low quality inoculum can be done with HRT as low as 15 or 12 hours. In this way, it is possible to reduce the starting-up period of these reactors down to 4 to 6 weeks, provided that the starting-up methodology is properly applied.

Keywords Domestic wastewater; start-up; UASB reactor

Introduction

The start-up phase of UASB reactors treating domestic sewage, has traditionally been a critical factor in achieving a wider application and acceptance of the technology. Initially, there was a scarce knowledge on the governing factors of the start-up and continuous operation phases of the process. Subsequently, the results obtained from new research and diverse experience at full-, pilot- and bench-scales, allowed a major understanding of most interactions taking place in these reactors. Hence, only in recent years it has been possible to draw out a clearer picture of microbiological mechanisms, hydrodynamic phenomena and their relationships with operational and control variables of the process (Noyola et al., 1998). Despite all the progress achieved, there are still areas of anaerobic biotechnology waiting to be developed. One of these is the improvement of anaerobic seeds (anaerobic sludge) in order to shorten the start-up phase of anaerobic reactors. The overall treatment process in a UASB reactor is described and controlled by the concepts and mechanisms of anaerobic digestion.

Regarding UASB’s start-up, it should be first inoculated with enough anaerobic sludge. Secondly, the reactor has to be initially fed at low loading rates but these have to be steadily increased up to the design loading rate. This period known as the start-up phase is one of the most important prerequisites for the continuous operation of the reactor under steady-state conditions. As pointed out by Chernicharo and Reis (1998), at the end of the start-up it is expected to have a concentrated sludge bed (4 to 10% w/w) and that is a concentration of 40,000 to 100,000 mg TSS/l in the lower part of the reactor.

The start-up of UASB reactors has been reported by different authors as a long and difficult process for the majority of wastewaters. This is due to the necessity of developing a high volume of biomass adapted to the specific conditions of each wastewater.
During the start-up phase there is a risk of organic overloading and if this happens the acid fermentation predominates over methanogenic fermentation. As a result, acidification of the reactor’s contents will inhibit methane production. Nevertheless, in the case of domestic sewage this situation rarely occurs as there is plenty of alkalinity (buffer capacity) in the water. Unlike other wastewaters, domestic sewage contains all needed bacterial populations for anaerobic digestion. For this reason, the start-up of the reactor can be carried out without inoculation (seeding of the UASB). Thus, just by feeding the reactor with raw sewage all the necessary anaerobic bacterial populations will develop naturally (van Haandel and Lettinga, 1994).

Although UASB reactors can be started up without inoculation, this factor helps to accelerate the start-up process. In case inoculation is chosen, it is recommended to use sludge from anaerobic reactors treating similar wastewaters. However, it is not always possible to obtain this sort of seed. In such a case and according to Noyola (1994) things like digested anaerobic sludge, activated sludge wastage, cattle manure, pond settled material or septic tank sludge can be used. Generally speaking, the seed selected must have enough biochemical activity and capacity to adapt to specific features of the wastewater. The higher the biochemical activity of the seed (inoculum) the shorter the start-up period will be. The start-up phase is finished once the reactor achieves a stable quality for the effluent under design conditions regardless of the variations in the influent quality. At this stage the initial amount of seed must have grown and improved its quality.

Based on the above considerations, this work shows the results obtained from the application of an innovative start-up methodology to a full-scale UASB reactor treating the domestic sewage of the municipality of Ginebra, Valle del Cauca region in Colombia. The results of this work contribute to the improvement of the start-up phase of UASB reactors used to treat domestic wastewaters.

Materials and methods

Experimental settings

The research was carried out in a full-scale UASB reactor located in the municipality of Ginebra, Valle del Cauca region in Colombia. The reactor was built on the premises of the Research Station on Wastewater Treatment and Reuse owned by the regional water company (ACUAVALLE S.A ESP). The UASB has a population equivalent of 5,000 inhabitants and currently treats an average wastewater flow of 8.0 l/s. The total volume of the reactor is 278 m³ (4.3 m height, 9.5 m length and 6.8 m width). It was designed to treat an average flow of 10.8 l/s with a HRT of 7.0 hours.

Start-up methodology

The first stage was the identification of a suitable anaerobic seed (inoculum) with good quality features. For this purpose, sludge samples from the bottom of an anaerobic pond (AP) located in the same area and treating the same wastewater were taken. The AP was divided in 4 sectors according to the intensity of biogas bubbling observed. A composite sludge sample was taken from each sector at depths varying between 1.0 to 3.0 m. All these samples were analysed for methanogenic activity (MA) and settleability.

The results of MA and settleability tests showed that sludge from the third section of the AP had the best properties for use as seed (MA = 0.186 gCOD/gVSS-day).

**Inoculation.** A total sludge volume of 55 m³ (equivalent to 20% of the reactor volume) with a concentration of 32.8 kgVS/m³ was pumped out from the AP to seed the UASB. Since the seed did not exhibit an optimum quality, it was necessary to improve it. For this purpose, the seeded sludge was subjected to a process called selective pressure in order to select
naturally the sludge particles with better properties. Meanwhile, the sludge particles with bad quality leave the reactor during the process.

Once the UASB was seeded, it was fed with wastewater under varying flow conditions as follows: the initial flow rate applied for 24 hours was the maximum allowed by the hydraulic capacity of the system. After this stage, the seeded sludge was exposed to a further selection process by the application of increasing upflow velocities as shown in Table 1. The latter procedure was aimed at improving the sludge settling properties.

Once the above upflow velocities were applied, the UASB was left in batch mode for 9 days. During this period the COD concentration was monitored in the supernatant until a reduction of 70% was detected in relation to the influent COD at the moment the batch period commenced. Total COD and filtered COD were both determined.

Start-up. This phase started with the continuous feeding of the reactor at a flow rate of 11.1 l/s corresponding to a HRT of 24.9 h. This low loading rate allowed a progressive adaptation of the biomass to the design loading rates. Furthermore, it also prevented sludge dragging by the effluent prior to the achievement of the design operating conditions.

Gradual flow increase. Once the continuous feeding started as described above, the influent flow rate was steadily increased, but keeping time intervals between successive increments. This step-by-step organic load increase is aimed at the continuous biomass adaptation to the final design conditions. The length of time intervals was defined by the stable behaviour of biogas production, effluent concentrations of COD and VFAs and the buffer index (BI) value under each operating condition. The main objective of this procedure was to take the reactor to a minimum HRT of 7 h (design conditions). Table 2 presents the applied flow rates and related HRT values during the start-up phase.

Monitoring programme. The behaviour of the reactor was controlled by monitoring the following parameters: sludge accumulation, organic matter concentration, TSS, settleable solids, pH, alkalinity, VFAs, nutrients concentration and pathogen content.

Results and discussion
Wastewater and inoculums characteristics
Wastewater. The domestic sewage from Ginebra arrive at the treatment site along with a fraction of rainfall waters since the sewerage network is combined. At the same time, the

<table>
<thead>
<tr>
<th>Flow rate (l/s)</th>
<th>Upflow Velocity (m/h)</th>
<th>HRT (h)</th>
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<tbody>
<tr>
<td>10</td>
<td>0.56</td>
<td>7.7</td>
</tr>
<tr>
<td>15</td>
<td>0.83</td>
<td>5.1</td>
</tr>
<tr>
<td>20</td>
<td>1.11</td>
<td>3.9</td>
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<tr>
<th>Average applied flow rate (m³/h)</th>
<th>Proposed HRT (h)</th>
<th>Real average HRT (h)</th>
<th>Standard dev. Q</th>
</tr>
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<tbody>
<tr>
<td>11.1</td>
<td>17</td>
<td>24.9</td>
<td>1.49</td>
</tr>
<tr>
<td>17.3</td>
<td>15</td>
<td>16.1</td>
<td>1.02</td>
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<td>19.5</td>
<td>13</td>
<td>14.3</td>
<td>0.72</td>
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<td>28.3</td>
<td>10</td>
<td>9.8</td>
<td>0.43</td>
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<td>33.6</td>
<td>8</td>
<td>8.3</td>
<td>0.56</td>
</tr>
<tr>
<td>41.6</td>
<td>6</td>
<td>6.7</td>
<td>0.86</td>
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raw wastewater from the municipal slaughterhouse discharges into the final sewer trench. These factors along with the local food sale activity alter the average composition of a typical domestic wastewater. Table 3 presents the average sewage characteristics at the Ginebra site.

*Inoculums (sludge seed).* Table 4 shows the features of the sludge seed before and after the start-up period. Notice that despite an apparent biomass loss (reduction of TSS and VSS) at the end of the start-up, there was, however, a substantial improvement in the MA and biogas production of the sludge. This fact proves the positive impact of washing the sludge seed according to the selective pressure methodology applied in this case. The loss of sludge observed may be attributed to the release of inert solids (reduction of TSS), release of raw organic matter stored in the sludge and the dragging of bad quality sludge particles (reduction of VSS). The factors mentioned can be the result of the combined effect of transient flows related to problems with the pumping station and also to a likely excessive sludge withdrawal. The latter situations occurred in the last 10 days of the start-up period.

Start-up methodology

*Evaluation of the batch period.* The organic matter present in the reactor at the beginning of the batch period was readily removed in less than 5 days. This fact showed that the biomass selected in the washing stage became completely activated as evidenced from the relatively high removal rate. It is arguable whether the batch period is essential in all cases. It would seem logical that a sludge seed already adapted to the wastewater does not need a further acclimatizing period as it will be able to utilize the substrate almost spontaneously. In other words, the metabolism and enzymatic reactions of the biomass are already suited to the substrate they have been living in. It is believed that this was the case in this study given the conditions already explained. In contrast, an anaerobic sludge seed exposed to a completely new substrate needs to readapt its enzymatic machinery to the new environment. Consequently this leads to a delay in the activation of removal processes.

*pH, VFAs and BI.* The raw wastewater quality was stable throughout the study as demonstrated by pH values around 7.0 in all samples. The variation of BI shown in Figure 1 confirms that buffer capacity was enough to neutralize the production of VFAs during the start-up period. Negative effects produced by accumulation of acidity were not observed as pH values were kept within an optimum range. These favourable environmental conditions allowed the coupling of bacterial groups responsible for hydrolysis, acetogenesis and methanogenesis. All these factors support the final conversion of VFAs into methane.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Before seeding</th>
<th>Beginning of start-up</th>
<th>End of start-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSS (g/l)</td>
<td>122,0</td>
<td>88,0</td>
<td>26,7</td>
</tr>
<tr>
<td>VSS (g/l)</td>
<td>59,0</td>
<td>39,5</td>
<td>10,2</td>
</tr>
<tr>
<td>Biogas production (l/m³)</td>
<td>-</td>
<td>12,9</td>
<td>60,0</td>
</tr>
<tr>
<td>Methanogenic activity (g COD/g VSS-day)</td>
<td>0,14</td>
<td>0,19</td>
<td>0,23</td>
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</table>
The reactor showed some instability signals explained by a slight accumulation of VFAs when HRT was around 10 h. Nevertheless, the reactor recovered its stability after a short period of time and again reduced the concentration of VFAs confirming the right balance of the anaerobic bacterial groups. It is considered that the UASB started working at its maximum capacity at HRT less than 10 h.

**Organic matter removal.** Figure 2 and Table 5 show the variations of COD concentrations during the start-up phase. Note that right from the beginning the effluent COD concentration was low and showed a stable pattern. This indicates the UASB was removing a considerable percentage of the applied organic load. However, most of the effluent COD was part of the soluble fraction indicating a low participation of biological removal processes in the overall performance. Hence, most of the removal at this stage was due to physical processes like solids entrapment, adsorption, settling and filtration. This observation is in close agreement with results reported elsewhere (Dean and Horan, 1995; Speece, 1996; Droste, 1997).

The high values of HRT at the beginning of the start-up produced low upflow velocities, which in turn enabled the presence of poorly mixed zones in the reactor. Consequently, the contact between active biomass and substrate was not optimal and the biogas production was minimal. However, as the HRT was gradually reduced the upflow velocities were increased producing a better contact pattern between biomass and substrate. A natural consequence of this was the improvement of soluble COD removal and the corresponding increase in biogas production. The latter shows the influence of upflow velocity in the mixing of the system. In this study it was found that the best removal efficiencies of soluble organic matter occurred at HRT values less than 9.8 h. This means that upflow velocities
higher than 0.50 m/h are beneficial to the hydrodynamic behaviour as well as to the biological process development in the vessel (Manzi, 2000).

The behaviour of the UASB becomes stable at HRT values less than 16 h. Other advantages related to the progressive increase in upflow velocity (i.e. reduction of HRT) are the even distribution of the sludge bed and its continuous quality improvement. This is due to a better contact between substrate and biomass since higher upflow velocities generate higher substrate dispersion throughout the reactor volume. Thus, transport phenomena to and from the cells becomes more efficient.

On the other hand, HRT values around 7.0 h (design condition) seemed to produce sludge wash out. However, the reactor quickly recovered its previous stability and in fact it was able to operate efficiently at a HRT of 6.7 h. It must be noticed that high upflow velocities (i.e. low HRT) produced sludge bed expansions at the top of the maximum limit. This factor increased the potential for sludge dragging and its consequent volume reduction.

The steady behaviour of the UASB even during variations of HRT, demonstrated that the reactor could easily start operation at HRT less than 24.9 h. The best functioning was obtained at 8.0 h HRT. Despite removal efficiencies not higher than 80%, the figures obtained were satisfactory for a domestic wastewater with high content of particulate matter. It may be argued that by applying the start-up methodology proposed in this study it is possible to shorten this stage to around 30–40 days. In this particular case the UASB could have started at 15 h HRT so that total start-up period would have been around 30 days.

**Sludge bed development.** At the beginning of the start-up phase and just after the batch period, the sludge was fully accumulated at the bottom of the reactor occupying only 11% of the total reactor’s volume. This was the consequence of compression sedimentation (type 4) since the reactor content was kept undisturbed for 9 days. This sludge compaction was observed during the first two HRT values (24.9 and 16.1 h). Meanwhile, for the following period when HRT varied between 14.3 and 9.8 h respectively, the sludge bed showed a sort of floating interface. This phenomenon may be related to the combined influence of the sludge compaction at very low upflow velocities followed by an increase in the hydraulic load (i.e. reduction of the HRT) which could move upwards the whole sludge mass. A behaviour of this sort was reported by Dean and Horan (1995) in a UASB reactor treating a combined wastewater (domestic sewage plus some industrial discharges) in Mauritius. It is also likely that biogas bubbles trapped in the compacted bed exerted a buoyant force helping the overall phenomena of sludge bed flotation.

A hydraulic shock load was applied to the reactor for a period of 4 hours in order to homogenise the reactor’s contents and eliminate the bed flotation. This procedure allowed the release of fine biogas bubbles and the washing out of bad quality sludge particles. As a result, the sludge bed was reselected and responded well from this moment up to the end of the start-up phase.

The sludge bed was expanded during the last step of start-up. The primary cause of this was the upflow velocity produced by the maximum applied flow rate (i.e. smallest HRT =

<table>
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<tr>
<th>Parameter</th>
<th>HRT (h)</th>
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<tbody>
<tr>
<td>Total influent COD (mg/l)</td>
<td>538</td>
<td>463</td>
<td>527</td>
<td>527</td>
<td>520</td>
</tr>
<tr>
<td>Effluent soluble COD (mg/l)</td>
<td>129</td>
<td>120</td>
<td>108</td>
<td>90</td>
<td>97</td>
</tr>
<tr>
<td>Maximum efficiency (%)</td>
<td>73</td>
<td>77</td>
<td>79</td>
<td>82</td>
<td>84</td>
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</table>
The fluidisation of the sludge bed was also helped by the increased biogas production recorded at this stage. On the other hand, a likely temporal accumulation of slow degradation material within the vessel could have occupied part of the effective volume rendering an increase in the total amount of the reactor’s solid material.

The development of the sludge bed can be seen in Figure 3. The volatile solids (VS) fraction tends to remain constant whilst total solids (TS) content showed a slightly increase over time. This trend may be attributed to the composition of the VS at the beginning of the start-up. VS were probably composed of a high organic matter fraction, which degraded over time and yielded a lower concentration of VS at the end. It is difficult to determine experimentally what fraction of the VS is biomass and what is raw organic matter. The determination of these fractions would be important to carry out a solids balance and work out the net biomass production. On the other hand, the augmentation of TS can be explained by the accumulation of influent TSS whose inorganic fraction may remain in the reactor. As discussed by Pavlostathis and Giraldo (1991), inert solids directly affect the substrate removal rate by hindering the mass transfer processes to and from the cells. This material eventually displaced active biomass by occupying a fraction of the reactor’s active volume.

The quality of the sludge was monitored by measuring the MA at different moments within the start-up period. Data from Table 4 indicate a gradual increase in MA showing the improvement of sludge activity. In other words, there was a qualitative evolution of the biomass leading to the establishment of the necessary anaerobic bacterial consortia.

Table 6 shows the results of settleability tests at the beginning and final stages of the period. The sludge clearly enhanced its settling properties throughout the start-up, as shown by settleability values that are much higher than upflow velocities in both cases. The steady increase in biogas production rate correlates well with augmentation of MA values. These data support the gradual activation and development of anaerobic bacterial consortia. The figure below shows that after a HRT=14 h the biogas production achieved its
maximum rate. Hence, the optimal operation point of the reactor is located somewhere between 14.0 and 8.3 h HRT.

The positive correlations between COD removal efficiency, biogas production and stability of the control variables demonstrated that the start-up period allowed for a healthy development of all anaerobic bacterial groups needed to treat the wastewater. The results of MA and sludge settleability at the end of start-up confirmed the overall improvement of sludge bed quality.

Conclusions
The start-up phase of the UASB at Ginebra (Colombia) was developed according to the planning and the methodology applied confirmed its advantages by shortening the start-up period down to only 9 weeks.

The selective pressure methodology (i.e. gradual increase of upflow velocity) proved to be an effective procedure to select the sludge with the best settling features. Consequently, low volumes of seed (inoculum) with poor quality can be used to start-up a reactor in a short period of time provided that sludge washing out has already been applied.

Based on initial and final MA results, it can be concluded that selective pressure methodology had a positive effect upon sludge activity. All the stages previous to the start-up can be developed in a maximum of one to two weeks.

The sludge bed evolution correlated well with increases in biogas production and upflow velocities along the start-up period. This finding suggests that start-up of a UASB reactor should commence with a minimum flow rate capable of homogenising the bed. On the other hand, very slow upflow velocities produce problems like sludge flotation, short-circuiting, dead zones and a generalised poor mixing pattern.

According to the experience reported in this paper, an UASB reactor treating domestic wastewater can be started with a bad quality seed in small quantities at HRTs varying between 12 to 15 h. Consequently, the start-up period can be reduced down to 4–5 weeks, which is an innovative result for full-scale reactors treating real wastewaters.

The implemented methodology was effective from a technical point of view but most importantly it presented a low cost. The latter due to the easiness of parameter determination and the low sampling frequency needed.

<table>
<thead>
<tr>
<th>HRT (h)</th>
<th>Upflow velocity (m/h)</th>
<th>Sludge settleability (m/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.9</td>
<td>0.17</td>
<td>3.18</td>
</tr>
<tr>
<td>8.3</td>
<td>0.52</td>
<td>4.09</td>
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Figure 4 Evolution of biogas production
Acknowledgements

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References


