Influence of HRT (hydraulic retention time) and SRT (solid retention time) on the hydrolytic pre-treatment of urban wastewater

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Abstract This work presents the results obtained from a study on the pretreatment of urban wastewater using a digester that acted as a system for the retention of solids (sedimentation-filtration), hydrolysis of the retained solids and acidification of the dissolved substances. After start-up (Phase I), the digester was operated at hydraulic retention times (HRT) of 4.4, 3.4 and 2.2 h and at solid retention times (SRT) of 24, 16 and 14 d, during Phases II, III and IV, respectively. The retention and removal of suspended solids (SS) was maintained slightly above 60%, independently of HRT and SRT. Conversely, eliminated chemical oxygen demand (COD) decreased slightly upon reducing HRT and SRT. The influence of these two parameters on the generation of volatile fatty acids (VFA) is more notable, reaching effluent VFA concentration of 29 (Phase II), 96 (Phase III), and 107 (Phase IV) mg COD/l. VFA to SS generation ratios were 0.13 (II), 0.35 (III), and 0.48 (IV) g VFACOD/g SS added. Optimum values were reached at an HRT of 2.2 h. Taking 100 kg influent COD as a base, the conversion of different kinds of COD was as follows (in kg influent:kg effluent): VFACOD(4:17), non-VFA soluble COD (45:23), VSSCOD (51:23). Simultaneously to these conversions, 2 kg VSSCOD are generated as purge stream and 35 kg COD are eliminated during the process.

Keywords Acidification; anaerobic digestion; hydrolysis; urban wastewater

Introduction
Anaerobic and aerobic treatments constitute two major processes for biological purification of wastewaters and biodegradable organic wastes. Anaerobic digestion is very favourable in terms of energy due to the fact that aeration is not necessary and biogas is produced which could be used as an energy source. Another major advantage is that sludge is produced at lower amounts than those obtained with aerobic processes. As a result, energy and sludge management costs are reduced, making anaerobic digestion the most frequently used biological system for treatment of waste effluents with medium and high organic loads. Due to the same reasons, anaerobic digestion also presents interesting possibilities for the treatment of diluted effluents such as urban and domestic residues (Jewell, 1987; Sanz and Fdz.-Polanco, 1990; Alaerts et al., 1993; Lettinga et al., 1993; Vieira et al., 1994; Kato, 1994; Ruiz et al., 1998).

For the treatment of domestic and urban wastewater, an interesting option is the separation of phases (Gonçalves et al., 1994; Wang, 1994), in which wastewater is first pretreated in a hydrolysis-acidification digester. This pretreatment could be followed by aerobic (activated sludge, lagoons) or anaerobic (methanogenic) biological systems. To achieve phase separation, raw wastewater is fed into an upflow sludge bed reactor, in which the HRT is sufficiently reduced, thus avoiding the conversion of certain organic fractions into methane. The SS settle in the digester, its retention time being higher than that of the liquid (SRT > HRT), forming a sludge bed, where soluble substances are also adsorbed. In this way, both the particulate and the soluble organic matter can undergo solubilisation and fermentation. These digesters are referred as hydrolytic upflow sludge bed (HUSB) reactors.

In a previous work (Ligero et al., 2000) the basic operation of a hydrolytic digester treating
domestic wastewater was presented. In this work mass balances are analysed, with special attention on the following subjects: excess sludge generation, nitrogen, phosphorus and sulphur compounds conversion, and the influence of HRT and SRT on digester behaviour.

Material and methods
Characteristics of the digester and analytical methods
A scheme of the digester used and its configuration, as well as a description of the analytical method employed, the characteristics of the influent wastewater and the inoculum were presented in a previous work (Ligero et al., 2000). The digester, with a total volume of 2 l, was operated in an upflow mode and at an ambient temperature of 20°C.

Definition and calculation of SRT
SRT is defined as the average time that different solid particles remain inside the digester. This concept includes the particles that enter the digester with the influent flow as well as those that are generated inside, and therefore, includes active solids (biomass) and inert suspended solids. The analytical programme includes the determination of two different parameters: total suspended solids (SS), and volatile suspended solids (VSS). Either of these parameters can be used to calculate SRT. We opted for using VSS values, thus excluding the possible interference of inorganic suspended solids.

Then SRT can be calculated as the ratio between total sludge mass in the digester, $M_x$ (as VSS), and sludge production rate, $F_{SP}$ (Henze et al., 1995).

\[
SRT = \frac{M_x}{F_{SP}}
\]

Where: $M_x$ is obtained as the product of sludge concentration in the digester and the digester volume,

\[
M_x = X_R \cdot V_R
\]

while $F_{SP}$ is defined as the sum of incoming sludge velocity into the digester with influent current and biomass generation velocity inside the digester,

\[
F_{SP} = Q_{vi}X_i + r_XV_R
\]

To calculate $F_{SP}$ it will be necessary to apply a sludge balance, in the following manner:

\[
Q_{vi}X_i + r_XV_R = Q_{ve}X_e + Q_{vp}X_p + A
\]

Where: A indicates the amount of sludge that in a determined period of time is accumulated in the digester, when its behaviour is not steady state, which concerns sludge flow. $Q_{ve}$ is the liquid flow, $X_e$ the effluent sludge concentration, $Q_{vp}$ the purge flow, and $X_p$ the sludge concentration in the purge.

Therefore, sludge production rate will be calculated as the sum of sludge lost in the effluent and the sludge removed from the digester in the purge, corrected, when necessary, for the variation of the amount of sludge inside the digester.

\[
F_{SP} = Q_{ve}X_e + Q_{vp}X_p + A
\]

Where: $X$ and $Q_x$ are mean values for each period, from the different specific measurements recorded, and A is the sludge accumulation per time unit inside the digester during that period. Therefore,

\[
X = \frac{\Sigma(X \Delta t)}{\Sigma \Delta t}
\]
\[ Q_V = \sum (Q_v \Delta t_i) / \sum \Delta t_i \]  
(7)

\[ A = V_R (X_{R\text{final}} - X_{R\text{initial}}) / \sum \Delta t_i \]  
(8)

Where: \( \Delta t_i \) is the time between consecutive measurements of the same variable within a wider operational period given by \( \sum \Delta t_i \), for which the mean property is calculated.

Excess sludge production (\( F_{\text{ESP}} \)) in the process is given by the sum of sludge content in the purge plus that accumulated in the digester.

\[ F_{\text{ESP}} = Q_{vp} X_p + A \]  
(9)

Operation strategy and control of SRT

The operation was divided into four long periods or phases (Phases I–IV), which were subdivided into shorter periods (Table 1). In Phase I the process was started, whereas Phases II, III, and IV differed fundamentally in the HRT applied. A constant feed flow rate was maintained throughout the operation, thus the different HRT values were obtained by varying digester volume and active height. The active reactor volume in each phase was 2.00 l (Phases I and II), 1.75 l (Phase III) and 1.15 l (Phases IV and V).

During Phases I and II sludge purging was not carried out, in order to increase the sludge concentration in the reactor. Thus, SRT was high, being controlled only by the efficiency of biomass retention inside the reactor. Periods IIa and IIb could be considered to be steady state, and used for the determination of the operational characteristics of the digester at an HRT of 4.4 h, and an average SRT of 20 d.

Period IIIa reflects the reactor operation transition from an HRT of 4.4 to 3.4 h. However, due to the elevated SRT at which the reactor operated, the adaptation of the sludge to the new HRT should not be considered complete until the end of period IIIb (that is, until a time of 4–5 times that of SRT). Therefore, only periods IIIc–IIIe can be considered as steady-state operation for the HRT of 3.5 h.

In order to maintain the digester sludge concentration at an approximately constant value and to control SRT, during Phases III and IV periodic purges were applied. The aim was to keep the sludge concentration close to 10 g VSS/l, and the sludge bed filling approximately 50% of the total active volume (that is, height of the sludge bed equal to 50% of active height). Purging was applied periodically, depending on the sludge bed growth observed.

Results

Influence of HRT on the conversion achieved in the digester

Figure 1 shows the cumulative frequency distribution of the main parameters (COD, SS, and VFA) for the influent and the effluent of the digester. This figure clearly shows the effect of the hydrolytic process on wastewater: retention of a significant quantity of SS, conversion into volatile fatty acids of hydrolysed and soluble compounds, and the elimination of a small percentage of COD.

Table 2 shows a summary of the results obtained for different hydraulic retention times. Effluent concentrations of SS and VSS were close to 90 and 80 mg/l, respectively, while SS and VSS removal was around 60%. The applied HRT did not show a significant influence on the behaviour of these parameters.

COD removal showed a different behaviour, being clearly affected by HRT, especially in the case of soluble COD removal. While for an HRT of 4.4 h CODs removal was round 30%, for an HRT of 3.4 and 2.2 h, it was in the range 15–20%. On the other hand, fats were eliminated to a great extent, independently of HRT, perhaps due to the fact that most of them were found as SS, and therefore were retained efficiently in the digester.
The generation of VFA was also affected by HRT, such that as HRT was decreased, the accumulation of VFA in the effluent was increased, within the experimental operation.
interval. At similar influent characteristics, the concentration of VFA tripled when going from an HRT of 4.4 h (29 mg COD_{VFA}/l) to an HRT of 3.4 h (96 mg COD_{VFA}/l), and even increased to 107 mg COD_{VFA}/l for an HRT of 2.2 h.

The biodegradation taking place into the digester can be evaluated from the point of view of VFA generation. The results (Table 2) show that for an HRT of 4.4 h, the generated VFA to added SS ratio was 0.13 mg COD_{VFA}/mg SS fed to the reactor. For an HRT of 3.4 h, this ratio rose to 0.35 mg COD_{VFA}/mg SS fed, and even reached 0.48 mg COD_{VFA}/mg SS fed at an HRT of 2.2 h. Generated VFA to removed SS ratios were 0.23, 0.60 and 0.75 mg COD_{VFA}/mg SS removed at HRT of 4.4 h, 3.4 h and 2.2 h, respectively.

At HRTs of 3.4 and 2.2 h, more than 86% of the VFA_{COD} contained in the acidified effluent corresponded to acetic acid, while propionic and butyric acids reached only small proportions, below 11% and 4% respectively. Therefore, the quantities of butyric acid found in the effluent were already present in the influent, such that butyric acid formation never resulted. In previous periods, at an HRT of 4.4 h, the contribution of acetic acid to total VFA was above 97%, in terms of VFA_{COD}.

Solids retention time (SRT) and production of excess sludge

Table 3 depicts the evolution of the sludge bed throughout the study, as well as other associated parameters, such as overall sludge concentration in the digester (X_p), total sludge mass (M_X), sludge production rate (F_{SP}), excess sludge production rate (F_{ESP}), and solid retention time (SRT).

Until period IIIa (day 279) no quantitatively significant sludge purges were performed, this producing a progressive increase of the sludge bed. On day 125 the concentration of suspended solids in the sludge bed was 25.4 g SS/l and 19.3 g VSS/l, leading to an overall concentration of 11.4 g VSS/l in the digester, in contrast to 4.4 g VSS/l at the start of operation. On day 279, overall VSS concentration inside the digester reached 14.7 g/l. From this point on, periodic purges were performed to maintain the overall concentration round 11 g VSS/l, with a maximum variation into the interval 10–15 g VSS/l, as shown in Table 3.

SRT was always above 13 d, but decreasing progressively from 24 d (period IIb) to 16–19 d (periods IIIc–IIIe) and, finally, to 14 d (period IV). Furthermore, these values of SRT corresponded to HRT of 4.4, 3.4 and 2.2 h, respectively. Thus, the evolution of conversion parameters, described above, were also influenced by the SRT applied.

In order to determine the excess sludge production, a sludge balance has been performed for the operational period from day 125 to 576. The amount of sludge purged in this period was 23.4 g VSS (excluded the last purge of day 576), while the amount of sludge inside the reactor decreased from 22.8 to 14.6, giving 8.2 g VSS of negative accumulation mainly due to the variation of active volume. Thus, the generation of excess sludge was 15.2 g VSS in this period. In terms of total suspended solids, the generation of excess sludge was 21.9 g SS. During this same period, 2745 g COD_t and 1012 g SS were fed to the reactor, of which
38% and 61% were eliminated, respectively, as calculated from the original data (Ligero et al., 2000). This way, sludge generation was 0.8% and 2.2% with respect to fed COD and fed SS, and 2.2% and 3.6% with respect to eliminated COD and eliminated SS. These data indicated an elevated biodegradation of solids retained in the reactor, however excess sludge production increases slightly when the HRT and SRT decreased.

SS and COD balances at the optimum HRT

Similar calculations for excess sludge production may be performed for the period IV, at an optimum HRT of 2.2 h, and the results combined with data from Table 2. Let us consider as a calculation base 100 kg COD that enter the digester, distributed in the following manner: 4 kg VFA COD, 45 kg COD different from VFA, and 51 kg VSS COD. For these 100 kg of COD that enter the digester, approximately 2 kg VSS COD are generated in the purge current, while 35 kg are eliminated during the process as a consequence of different mechanisms. About 63 kg COD leave the system in the effluent, distributed in the following manner: 17 kg VFA COD, 23 kg COD different from VFA, and 23 kg VSS COD.

If 100 kg SS fed into the digester during Phase IV are taken as base, we observe that only 37 kg SS are going to remain in the effluent and 3 kg SS in the purge current, 60 kg SS being eliminated by the diverse bioconversion processes.

Conversion of compounds with heteroatoms

Apart from the parameters discussed before, the behaviour of total Kjeldahl nitrogen (TKN), ammonia (\(NH_4^+\)), sulphates and phosphates were also followed. The results are shown in Table 4.

In Phase II, elimination of nitrogen (10–40% of TKN) and ammonia (15–20%) was observed, implying the existence of a partial nitrification–denitrification process. At the same time, phosphate concentration increased during the process, going from 7–8 mg/l in the influent to 12–13 mg/l in the effluent. This indicates the probable existence of degradation of phosphorus containing organic matter. Lastly, there was a partial elimination of sulphates, the possible sulphate reduction contributing slightly toward COD elimination.

Periods IIIa and IIIb correspond to the transition to new operational conditions, since we start from a biomass that is adapted to a longer HRT, that as a consequence of the elevated SRT, can only adapt slowly to the new HRT. Therefore, period IIIa maintains the ability for total nitrogen elimination that will disappear in period IIIb. At the same time, phosphate generation and sulphate reduction will not be modified until the end of period IIIb. This is in accordance with the elevated SRT values of about 20–30 d, and indicates that a period of 4 or 5 times the SRT is necessary for the transition to the new steady state.

During steady-state operation at an HRT of 3.4 h and SRT of 15–20 d, periods IIIc–IIIe, TKN elimination was practically null, while excess ammonia appeared in the effluent, where concentrations were 50–100% higher than those in the influent. Therefore, hydroly-

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**Table 3 Characteristics of sludge bed, sludge generation and SRT**

<table>
<thead>
<tr>
<th>Operation day</th>
<th>Sludge bed</th>
<th>Digestor</th>
<th>Purge</th>
<th>Mx</th>
<th>FESP</th>
<th>ESP</th>
<th>SRT</th>
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<tr>
<td></td>
<td>H cm</td>
<td>SS g/l</td>
<td>VSS g/l</td>
<td>X_m gSS/l</td>
<td>X_n gVSS/l</td>
<td>Volume ml</td>
<td>gVSS/d</td>
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<td>14.7</td>
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<td>16.4</td>
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<tr>
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<td>27.3</td>
<td>18.8</td>
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<td>600</td>
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<tr>
<td>576</td>
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<td>14.4</td>
<td>18.7</td>
<td>12.7</td>
<td>350</td>
<td>14.60</td>
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</table>
sis of protein material still existed, which lead to the generation of ammonia, but the nitrification–denitrification process almost totally disappeared. Similarly, the variation in phosphate concentrations became insignificant and sulphate reduction was restricted, being only 5–16% of influent sulphate during these periods.

For period IV, at the lower HRT of 2.2 h, one would expect a slight reduction in the extent of the processes taking place. This was observed in the conversion of nitrogen, since ammonia formation was reduced, indicating a reduction in the biodegradation of protein compounds.

Discussion
This work analyses the direct hydrolysis-acidification of urban wastewaters in an upflow sludge bed digester operated successively at an HRT of 4.4 h (Phase II), 3.4 h (Phase III) and 2.2 h (Phase IV), and at an SRT of 24, 16 and 14 d, respectively. The digester acted as a filter-settler, retaining efficiently a great part of influent SS (more than 60%), independently of HRT. In addition to the mechanical retention of SS, part of the soluble substances could probably be retained on the sludge bed by absorption. The result was the existence of a solid phase consisting of material in suspension and absorbed substances, and a liquid phase flowing through the solid phase. Both phases contain a biodegradable organic fraction and an inert fraction.

The experimental results show that SS retention was not influenced by HRT, such that the extent in which this fraction was hydrolysed and fermented to VFA depended mainly on SRT. In this situation, the results of the degradation process of SS retained in the digester should coincide with those obtained from the acidification studies of primary sludge.

Studies on the hydrolysis of primary sludge (Elefsiniotis and Oldham, 1994 a, b, c) indicate that SRT had little effect on the hydrolysis of carbohydrates and lipids (5.8% increase when going from 5 to 15 d), while with proteins the increase was from 37% at an SRT of 5 days to 55% hydrolysis at an SRT of 20 d. In this study, SRT was typically in the range 14–24 d, suggesting that its variation did not affect the extent of degradation of the different influent organic compounds, guaranteeing an elevated degradation of all components, particularly the protein fraction. The latter is in agreement with the increase observed in effluent ammonia concentration as compared to influent concentration during Phases III and IV.

These studies (Elefsiniotis and Oldham, 1994 a, b, c) reported that maximum VFA...
production was about 0.22–0.25 mg VFA/mg VSS added, and SRT did not affect the hydrolysis of particulate COD (or % VSS removal), although conversion processes of soluble molecules into VFA could be more influenced by SRT. In this work, the acidification ratio obtained at HRT of 2.2 h was 0.45 mg VFA\textsubscript{COD}/mg SS added or 0.55 mg VFA\textsubscript{COD}/mg VSS added, much higher than maximum ratios for primary sludge reported in the reference. This indicates that a large part of VFA formed are obtained from acidification of influent soluble fraction or VSS that are not retained in a primary decanter, giving direct acidification of urban wastewater an advantage over separation and later acidification of primary sludge. The greatest extent of hydrolysis and acidification was obtained at an HRT below 3.4 h, the conversion even improving slightly when approaching an HRT of 2 h.

VFA rates obtained could be influenced by other processes like conversion of heteroatoms containing compounds, especially nitrogen and sulphur. The conversion of such compounds slightly contributed to COD elimination, although it was more significant in Phase II and in transition periods of Phase III. Another process that could contribute to COD removal was methanogenic respiration. Although net biogas production was not observed this possibility couldn’t be rejected, so that small amounts of methane could leave the system in dissolution. Thus, it seems reasonable that the decline of these processes with the reduction of HRT, confirmed experimentally in the case of conversion of nitrogen and sulphur compounds, could be the main cause for the reduction observed in the percentages of COD elimination and the increase in VFA effluent concentrations.

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References