Long-term evaluation of a sequential batch reactor (SBR) treating dairy wastewater for carbon removal

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Abstract Many dairy industries have been using SBR wastewater treatment plants because they allow optimal working condition to be reached. However, to take advantage of SBR capabilities, strong process automation is needed. The aim of this work is to study the factors that influence SBR performance to improve modelling and control. To better understand the whole process we studied the kinetic modelling, the carbon removal mechanism and the relation between reactor performance, aerobic heterotrophic activity and bacterial population dynamics (by terminal restriction fragment length polymorphisms of 16S rDNA, T-RFLP). The heterotrophic activity values presented high variability during some periods; however, this was not reflected on the reactor performance. As sludge health indicator, the average activity in a period was better than individual values. Although all the carbon removal mechanisms are still unclear for this process, they seemed to be influenced by non-respirometric ways (storage, biosorption, accumulation, etc.). The variability of heterotrophic activity could be correlated with the bacterial population diversity over time. Despite the high variability of the activity, a simple kinetic model (pseudo ASM1) based on apparent constant parameters was developed and calibrated. Such modellisation provided a good tool for control purposes.

Keywords Kinetic modelling; microbial activity; population dynamics; sequential batch reactor; T-RFLP

Introduction Many dairy industries utilise SBR treatment plants in order to achieve the wastewater required depuration (Castro et al., 2001; Garrido et al., 2001). This technology appears as a feasible alternative which allows continuous control and regulation of its critical operating parameters (Chang and Hao, 1996; Artan and Orhon, 2005). The SBR process is useful for small as well as large plants, even when continuous or discontinuous effluent generation is present (Artan and Orhon, 2005). However, to take advantage of the SBR capabilities, a strong process automation and control is needed (Artan and Orhon, 2005). In this sense, the kinetic modelling and population dynamics analysis in an SBR process become of critical importance.

The aim of this work is to study the factors that influence SBR performance to improve the modelling and control of the system. To obtain an insight in the whole processes we studied the kinetic modelling, the mechanisms of carbon removal by degradation of heterotrophs and by non-respirometric ways (storage, biosorption, accumulation, etc.). Additionally, we investigated the relation between the reactor performance, the aerobic heterotrophic activity and the bacterial population dynamics along different periods of the SBR.

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Methods

Reactor description and operating conditions

The operation of a 15 L SBR for carbon removal fed with dairy wastewater was monitored for 2 years. The influent (average composition: 3,000 gCOD.m$^{-3}$, 60 g TKN.m$^{-3}$, 80 gN-NO$_3^-$.m$^{-3}$) was obtained by whole milk dilution and sodium nitrate addition, in order to simulate nitric acid and sodium hydroxide washings routines employed in many dairy processes. The reactor was inoculated with a laboratory batch culture grown with diluted milk. The SBR (two cycles by day) was operated with 20 days of biomass retention time ($t_d$), a biomass concentration between 2,000–4,000 gVSS.m$^{-3}$, and maintained at 20 ± 2°C. The reactor operation was fully automatic and it was controlled by a PLC/SCADA environment. The different strategies employed are shown in Table 1.

During P1, a set of experiments were performed in order to calibrate a simple phenomenological model for control purposes. According to the high C/N ratio (50) of the influent, anoxic and aerobic carbon removal would be the main processes to be modelled. The adopted kinetic expressions are detailed further. In this period, filamentous bulking was the sole operative problem found in the reactor. To solve it, a cationic polyelectrolyte flocculant (Praestol 644, Stockhausen GmbH & Co) was periodically added during P2. In P3, organic load was slowly increased at 0.2 gCOD.m$^{-3}$.d$^{-1}$.week$^{-1}$ in an attempt to evaluate the maximal treatment capabilities of the SBR. However, the increased oxygen demand (higher biomass concentration) became a limiting factor. Consequently, during P4 the organic load was maintained at the initial value and the aeration time was reduced in order to evaluate the best working condition achievable in a conventional strategy (not controlled). During P5, a sub-optimal control law to reach a minimal cycle reaction time was implemented. The construction of this algorithm was based on the model calibration made in P1. The resulting aerobic time was shorter than the aerobic time applied during P4.

Kinetic description (pseudo ASM1)

Anoxic reaction (denitrification).

$$r_{V_{XH}} = (\mu_{aN} - k d N) \cdot X_H$$

$$\mu_{aN} = \mu_{aN \max} \cdot \left[ \frac{S_C - S_{C_{\min}}}{K_{C1} + S_C - S_{C_{\min}}} \right] \cdot \left[ \frac{S_{NO}}{K_{NO} + S_{NO}} \right]$$

$$r_{V_{SC}} = \frac{1}{Y_{HN}} \cdot \mu_{aN} \cdot X_H$$

$$r_{V_{SNO}} = -\frac{1}{Y_{S}} \cdot \mu_{aN} \cdot X_H$$

Table 1 Operating conditions for the SBR

<table>
<thead>
<tr>
<th>Period</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5***</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration (cycles)</td>
<td>200</td>
<td>300</td>
<td>100</td>
<td>175</td>
<td>175</td>
</tr>
<tr>
<td>Anoxic phase (h/per cycle)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1.2–1.4</td>
</tr>
<tr>
<td>Aerobic phase (h/per cycle)*</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>6</td>
<td>2.8–4.8</td>
</tr>
<tr>
<td>Settling time (h/per cycle)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Draw + idle time (h/per cycle)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>4.0–5.0</td>
</tr>
<tr>
<td>Organic load (kgCOD.m$^{-3}$.d$^{-1}$)</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8–1.6</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Special condition</td>
<td>Flocculant addition**</td>
<td>Control law application</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Sludge purge at the end
**Periodical polymer use
***Global anoxic and aerobic time (two aerobic phases separated by an anoxic phase)
Aerobic reaction.

\[ r_{V_{SC}} = (\mu_h - kd)X_{H} \quad r_{V_{sc}} = -\frac{1}{Y_{H}} \cdot \mu_h \cdot X_{H} \]

\[ \mu_h = \mu_{\text{imnax}} \frac{SC - SC_{\text{min}}}{K_{Ch} + SC - SC_{\text{min}}} \cdot \frac{SO}{K_{Ch} + SO} \]

Analytical measurements

An almost complete evaluation of SBR performance in more than 30 cycles was made. Total and volatile suspended solids (TSS and VSS), biochemical oxygen demand (BOD\textsubscript{5}), COD\textsubscript{s}, total kjeldhal nitrogen (TKN), NO\textsubscript{2}X, sludge volumetric index (SVI) were carried out according to Standard Methods (1995). Temperature (T), pH, DO, redox potential (ORP) were measured with probes and oxygen transfer coefficient (kla) was determined by a respirometric in situ transient method. Biomass heterotrophic activity (BHA) was measured by taking a sludge sample, kept aerated for 12 h without substrate addition and afterwards acetate (saturating concentration) was added and oxygen consumption rate was measured. Bacterial population dynamics was evaluated by T-RFLP of 16S rDNA according to Braker et al. (2001) using MspI and HhaI as digestion enzymes. Analyses of results were performed according to Dunbar et al. (2001). Diversity (Shannon H Diversity and Dominance D indexes) and Cluster Analyses were performed using PAST (PAST - PAleontological STatistics, ver. 1.42 Øyvind Hammer, D.A.T. Harper and P.D. Ryan).

Results and discussion

Reactor performance

Soluble COD and TKN removal efficiencies were in the range of 90–99\% during the reported period. Effluent soluble COD was always less than 90 g.m\textsuperscript{-3} and the lowest measured value was 54 g.m\textsuperscript{-3}. According to Orhon et al. (1993), this limit is related to the generation of COD-residual fractions. Soluble BOD\textsubscript{5} and NO\textsubscript{2} in the effluent were less than 15 g.m\textsuperscript{-3}, and effluent TKN was always less than 5 gN.m\textsuperscript{-3}. From these results, it can be concluded that the SBR performance was acceptable in the studied period.

Biomass heterotrophic activity

BHA varied between 100 and 1,200 mgO\textsubscript{2}.gVSS\textsuperscript{-1}.d\textsuperscript{-1} (Figure 1). A trend of increasing BHA (despite the daily variability) can be observed from P3 to P5, which was briefly perturbed during partial reinoculation in P4. The daily values presented high variability (up to 1,000\%). Did this variability reflect the variability in the reactor operation? If such behaviour was observed, a set of “constant” kinetic parameters should not be useful for control purposes.

In order to evaluate maximum soluble substrate removal rate (v\textsubscript{CODs}) variability, COD profiles were employed during reactor cycles. The results are shown in Table 2. Since BHA had a mean value of around 200 mgO\textsubscript{2}.gVSS\textsuperscript{-1}.d\textsuperscript{-1} in P2 and increased from 400 to 1,000 mgO\textsubscript{2}.gVSS\textsuperscript{-1}.d\textsuperscript{-1} in P5 (Figure 1), the corresponding v\textsubscript{CODs} should be two to five times higher for P5 than for P2. Even though the disappearance of soluble COD was faster for P5, it was only 1.5 times higher (Table 2). From P2 to P5, the increase of v\textsubscript{CODs} correlated with the increase in average BHA, but the values were not as high as expected. Thus, despite the high BHA variability, a model based on constant apparent
parameters could still be useful for control purposes if soluble COD profile is used for model calibration.

Even when the model could be acceptable for control, the mechanism of soluble COD consumption remains unclear. During P2, the BHA varied between 100 and 400 mgO₂·gVSS⁻¹·d⁻¹. Therefore, the corresponding maximum substrate removal rate (neglecting endogenous consumption) should be 150 to 1,600 mgO₂·gVSS⁻¹·d⁻¹ (assuming a yield coefficient of 0.6 to 0.8 gCOD·gCOD⁻¹). However, the observed real COD consumption, 3,400 to 6,900 mgO₂·gVSS⁻¹·d⁻¹, was much higher. Other periods showed the same tendency. Soluble COD consumption seems to be controlled by other phenomena as well. One explanation for this could be the storage, biosorption or accumulation processes by bacteria inside the reactor (not measured by the respirometric test used to determine BHA) which will necessary yield a higher vCODs compared with activity values (Goel et al., 1998; Beccari et al., 2002; Karahan-Güll et al., 2002).

Microbial community analysis and BHA

In Figure 2 the relative abundance of bacterial terminal restriction fragments (T-RFs), the diversity and dominance indexes calculated from T-RFLP data and cluster analysis are presented. Similar results were obtained with digestion with the other enzyme *Hha* I (data not shown).

Regarding microbial community analyses, the Shannon H Diversity and Dominance D indexes showed a high bacterial diversity and low dominance during P1, P4 and P5. These results could explain the high BHA variability found in these periods since different bacterial species could have different acetate consumption rates. This result suggests that average BHA is a better indicator than individual BHA measurements for sludge health evaluation in case of sludge with shifting bacterial populations.

Table 2 Maximum substrate removal rate during reactor cycles for P1, 2, 4 and 5

<table>
<thead>
<tr>
<th>Period</th>
<th>No cycles evaluated</th>
<th>vCODs (mgCOD·gVSS⁻¹·d⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>P1</td>
<td>8</td>
<td>3,700</td>
</tr>
<tr>
<td>P2</td>
<td>5</td>
<td>4,700</td>
</tr>
<tr>
<td>P4</td>
<td>4</td>
<td>6,250</td>
</tr>
<tr>
<td>P5</td>
<td>6</td>
<td>7,180</td>
</tr>
</tbody>
</table>
The flocculant addition in P2 strongly affected the BHA (Figure 1). During P2 the microbial community analyses showed that the population diversity decreased and dominance increased (Figure 2B), but the average BHA decreased compared to P1. In P3 a different bacterial community from P1 and P2 established into the reactor (Figure 2C).

After the maintenance stage of the SBR (between P3 and P4), a partial reinoculation with native sludge was carried out in P4 in order to improve the settling properties. The average BHA and the population diversity increased in this period, suggesting that new species were added with the inoculum (Figure 2B and C). However, the cluster analysis revealed that the bacterial community during P4 and P5 was similar to that of P3 but different from P1 and P2.

During P5 the community analysis revealed that a more diverse but more stable bacterial community developed while average BHA strongly increased. As aeration phase was diminished for P4 and P5, the reduction of real endogenous aerobic time could
explain the activity increase through an improvement in the biomass viable fraction (Siegrist et al., 1999).

**Kinetic model and its control application**

The model was calibrated and validated with data from P1. Complete data values from the calibration algorithm are detailed in Ferrari et al. (in preparation). Despite this, Figure 3 illustrates the fitting degree reached at this stage for two cycles. A sub-optimal control law to reach a minimal cycle reaction time was implemented. The construction of this algorithm was based on the previous model calibration (Ferrari et al., in preparation). In Figure 4, COD and NO\(_x\) concentration profiles of a cycle during P5 are shown. According to these data, the time phases predicted by the model were adequate to perform the complete reactions. Despite this, aerobic time was overestimated. Thus, the kinetic modelling carried out could yield a good tool for control purposes (robust and simple algorithm).

**Settling properties**

Along the 2 years of SBR operation, the sludge settling properties were in agreement with the data shown in Table 3. As can be seen, the sludge volumetric index was only acceptable after polymer addition or nitrogen management in the system (5 gTKN.m\(^{-3}\) urea addition in the influent). Therefore, there were no risks of biomass losses at drawing stage. Because the polymer addition could simultaneously reduce average activity values (sludge health impact), the nitrogen management was considered the best condition to overcome bulking problems.

**Table 3** Sludge volumetric index

<table>
<thead>
<tr>
<th>Period</th>
<th>Average SVI measured (mL.gTSS(^{-1}))</th>
<th>SVI Target (mL.gTSS(^{-1}))</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>&gt; 150</td>
<td>150*</td>
<td>Bulking</td>
</tr>
<tr>
<td>P2</td>
<td>&lt; 150</td>
<td></td>
<td>Flocculant addition</td>
</tr>
<tr>
<td>P3</td>
<td>~ 150</td>
<td></td>
<td>Stable condition</td>
</tr>
<tr>
<td>P4</td>
<td>&gt; 150</td>
<td></td>
<td>Bulking</td>
</tr>
<tr>
<td>P5</td>
<td>&lt; 150</td>
<td></td>
<td>N–limitation elimination</td>
</tr>
</tbody>
</table>

*Grady and Lim (1998)
Conclusions
Although all the carbon removal mechanisms are still unclear for this process, they seem to be influenced by non-respirometric ways (storage, biosorption, accumulation, etc.). The average heterotrophic activity in a period was found better as a sludge health indicator than the individual values. The variability of heterotrophic activity could be correlated with the bacterial population diversity. The predominance of different species with particular metabolic behaviour could explain the high variability of the heterotrophic activity along time. Reduction of the extent of endogenous aerobic processes increased the average activity, most likely due to an improvement in the biomass viable fraction. The sludge settling properties were only acceptable through the elimination of the nitrogen limitation in the reactor. Despite the high activity variability, a simple kinetic model (pseudo ASM1) based on apparent constant parameters was developed and calibrated. Because of its simplicity, such modellisation provided a good tool for industrial control purposes.

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References