The impact of slowly biodegradable organic compounds on the oxygen uptake rate in activated sludge systems
J. Drewnowski

ABSTRACT

The hydrolysis process of slowly biodegradable substrate ($X_S$) has an impact on the efficiencies of nutrient removal in activated sludge systems. Measurement of oxygen utilization rates (OURs) and corresponding chemical oxygen demand (COD) is accepted as a very useful tool to reflect the consumption of biodegradable substrates. The influence of the $S_S$ fraction in biological wastewater treatment systems has been extensively investigated, but little information is known about the effects of $X_S$ on OUR. The aim of this study was to determine the immediate effects of particulate and colloidal ($X_S$) biodegradable compounds on oxygen utilization for a full-scale process mixed liquor from a large wastewater treatment plant located in northern Poland. Since it is difficult to distinguish $X_S$ in a direct way, a novel procedure, based on the standard batch tests, was developed and run in parallel reactors with settled wastewater (SWW) and pretreated SWW samples. Two types of aerobic OUR experiments with low and high substrate/biomass ($S_0/X_0$) concentration, were carried out with the SWW without pretreatment, and pretreated with a coagulation–flocculation (C–F) method. The removal of colloidal and particulate fractions by C–F resulted in reduced process rates. The major discrepancy in the rate reductions (over 300% referred to the OUR$_{max}$) was observed during the OUR batch test with high $S_0/X_0$ ratio.

Key words | activated sludge, batch test, biological nutrient removal, hydrolysis, OUR, slowly biodegradable substrate

INTRODUCTION

Municipal wastewater is composed of a mixture of organic substrates that have to be described separately in order to improve complex wastewater characteristics and achieve high efficiencies of nutrient removal in activated sludge systems. Ekama & Marais (1979) were the first to divide wastewater into distinct biodegradable fractions that are degraded at two different rates. The readily biodegradable ($S_S$) fraction consists mainly of soluble organic compounds and the slowly biodegradable ($X_S$) fraction consists of large molecules, colloids and particles. According to the literature data (e.g., Orhon et al. 1997; Lagarde et al. 2005), municipal wastewater after primary treatment contains $S_S$ and $X_S$ substrates in the amounts of approximately 10–30% and 40–60% of total chemical oxygen demand (COD), respectively. An investigation in four municipal wastewater treatment plants (WWTPs) in northern Poland revealed that colloidal and particulate fractions constituted even more than 60% of total COD (Czerwionka et al. 2008). These two physical forms mostly contain $X_S$, which can be taken up and degraded by microorganisms after hydrolysis to $S_S$ (Levine et al. 1985).

In traditional opinion, the process of hydrolysis summarizes all mechanisms and complicated reactions inside the microorganism flocs by means of extracellular enzymes that make $X_S$ available for bacterial growth (known in the literature as a transformation of $X_S$ to $S_S$) in wastewater treatment applications (Henze et al. 1987; Melcer et al. 2003). Recent experimental observations indicate, however, that the removal of particles is not instantaneous and is better described by flocculation–hydrolysis rather than a one-step hydrolysis (Jimenez et al. 2005). The latest reported full-scale data on the effects of particulate and colloidal ($X_S$) substrate on process performance are ambiguous and suggest that different behaviours may result from complex interactions.
occurring in the activated sludge systems (van Veldhuizen et al. 1999; Tas et al. 2009; Tuncal et al. 2009; Puig et al. 2010). Consistently, in biological nutrient removal (BNR) WWTPs, the influence of $X_S$ in the form of colloidal and particulate organic compounds is important in terms of optimization of sedimentation and chemical precipitation in primary clarifiers (i.e. balancing between the efficiency of nutrient removal in the bioreactor and biogas production in the digester). The particulate and colloidal organic fractions and associated hydrolysis process of $X_S$ also have an impact on the efficiencies of nutrient removal in activated sludge systems. In the delicate balance between the organic carbon, nitrogen and phosphorus content in the wastewater, the amount of organic carbon is meaningful only if it is expressed in terms of various fractions with different mechanisms and rates of biodegradation. In this respect, measurement of oxygen utilization rates (OURs) and corresponding COD is accepted as a very useful tool to reflect the consumption of biodegradable substrates and evaluation of biological treatment processes in activated sludge systems (Henze 1992). The influence of the $S_S$ fraction in biological wastewater treatment systems has been extensively investigated, but little information is known about the effects of $X_S$ on the OUR. The aim of this study was to determine the immediate effects of particulate and colloidal ($X_S$) biodegradable compounds on oxygen utilization for a full-scale process mixed liquor originating from large WWTPs. Unfortunately, it is difficult to distinguish $X_S$ from wastewater in a direct way, therefore a novel procedure was developed and implemented by Drewnowski & Makinia (2011). This follow-up study was based on the comparison of standard OUR batch tests and corresponding COD and the influence of the slowly biodegradable substrate from wastewater indirectly (Figure 1). In the first reactor (R1), the process biomass (‘fresh’ returned activated sludge – RAS) was mixed with the SWW without pretreatment (containing soluble, colloidal and particulate organic fractions), whereas the SWW after coagulation–flocculation (C–F) was used in the second reactor (R2). The latter sample of wastewater, containing only a soluble organic fraction, was prepared according to the rapid physical–chemical method of Mamais et al. (1995). That method is based on the rationale that membrane filtration of a sample that has been flocculated (by precipitating with ZnSO$_4$ at pH 10.5) will remove the colloidal particles from a filtrate leaving only truly soluble organic matter. After removing colloids and particulates, the pH was adjusted to its original value by adding 6 mol/L HCl. Batch tests were run according to a similar concept proposed earlier by Goel et al. (1999). Laboratory experiments were carried out in a specially designed and constructed experimental set-up consisting of two

### MATERIALS AND METHODS

#### Study site

The study was conducted at the ‘Wschod’ WWTP, located in the city of Gdansk during an experimental series comprising the winter and summer months. The samples were collected in the study period March–July 2008 (Table 1). The ‘Wschod’ WWTP is one of the largest facilities in northern Poland located upon the Baltic Sea, which treats wastewater originating from the city of Gdansk and adjoining communities. During the period of the study, the biological step consists of six parallel bioreactors, which run in the Modified University of Cape Town process configuration, connected to 12 circular secondary clarifiers.

#### Sample preparation and procedures of laboratory experiments

The 24-hour composite samples of the SWW entering the full-scale bioreactors were used in the experiments. The laboratory experiments were conducted in two parallel batch reactors in order to distinguish the slowly biodegradable substrate from wastewater indirectly (Figure 1). In the first reactor (R1), the process biomass (‘fresh’ returned activated sludge – RAS) was mixed with the SWW without pretreatment (containing soluble, colloidal and particulate organic fractions), whereas the SWW after coagulation–flocculation (C–F) was used in the second reactor (R2). The latter sample of wastewater, containing only a soluble organic fraction, was prepared according to the rapid physical–chemical method of Mamais et al. (1995). That method is based on the rationale that membrane filtration of a sample that has been flocculated (by precipitating with ZnSO$_4$ at pH 10.5) will remove the colloidal particles from a filtrate leaving only truly soluble organic matter. After removing colloids and particulates, the pH was adjusted to its original value by adding 6 mol/L HCl. Batch tests were run according to a similar concept proposed earlier by Goel et al. (1999). Laboratory experiments were carried out in a specially designed and constructed experimental set-up consisting of two

### Table 1 | Characteristics of the studied ‘Wschod’ WWTP in Gdansk during the period of the study, March–July 2008

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PE [m$^3$/d]</th>
<th>Q [m$^3$/d]</th>
<th>SRT [d]</th>
<th>MLSS [g COD/m$^3$]</th>
<th>COD [g COD/m$^3$]</th>
<th>SCOD [g P/m$^3$]</th>
<th>TP [g N/m$^3$]</th>
<th>TN [g N/m$^3$]</th>
<th>N-NH$_4$ [g N/m$^3$]</th>
<th>N-NO$_3$ [g N/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>574,000</td>
<td>81,600</td>
<td>19.0</td>
<td>5.3</td>
<td>1,090</td>
<td>278.0</td>
<td>13.3</td>
<td>81.0</td>
<td>58.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Effluent</td>
<td>48.1</td>
<td>0.6</td>
<td>11.1</td>
<td>1.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
parallel, plexiglass batch reactors (maximum volume of 4.0 dm$^3$), a control system and computer (Figure 1). The reactors were equipped with electrodes for continuous monitoring of pH, oxidation reduction potential (ORP), temperature ($T$) and dissolved oxygen (DO). The automated control system maintained the desired DO concentration and temperature in the reactors. The temperature was set close to the actual set point ($T = 13^\circ$–$20^\circ$ C) process in the ‘Wschod’ WWTP full-scale bioreactors. The experimental data (pH, DO, T, ORP) were collected online by computer from a control box and probes installed in each batch reactor.

Two kinds of batch tests with low and high $S_0/X_0$ ratio were used to determine OURs under aerobic conditions (DO = 6 mg/dm$^3$). In the so-called ‘low $S_0/X_0$ ratio’ OUR measurements the concentration of actual mixed liquor suspended solids (MLSS) in the reactors varied between 2 and 3 [g/dm$^3$], whereas in the so-called ‘high $S_0/X_0$ ratio’ OURs were 0.1–0.7 [g/dm$^3$]. An hour before starting the OUR measurement, nitrification inhibitor (allylthiourea – ATU) was added to the fresh RAS from WWTP in the amount of 10 mg/dm$^3$. The measurement was conducted for 7 h and samples of the mixed liquor ($V = 50$ cm$^3$) were withdrawn at the frequency of 10–60 min, filtered under vacuum pressure on the 1.2 μm Whatman GF/C filter and analysed for COD. Total suspended solids (TSS) and volatile suspended solids (VSS) concentrations were measured in the RAS at the beginning of the test.

Analytical methods

Total and volatile suspended solids were measured by the gravimetric method according to Polish Standards (PN-72/C-04559). The total and/or soluble COD, PO$_4$-P, NO$_3$-N and NH$_4$-N were analysed using Xion 500 spectrophotometer (Hach Lange GmbH, Germany). The analytical procedures, which were adapted by Hach Lange GmbH, followed the APHA (1992) methods.

RESULTS AND DISCUSSION

Characteristics of the wastewater samples from the studied plant

The average value of total COD in the wastewater samples from the ‘Wschod’ WWTP was 671 (±73) [g COD/m$^3$] including soluble COD, SCOD = 229 (±28) [g COD/m$^3$] vs. non-soluble (colloidal and particulate) COD, XCOD = 442 (±51) [g COD/m$^3$]. The soluble fraction, accounting for 34% of total COD (average value in eight wastewater samples), was used in the batch experiments (R2) during the winter/summer 2008 study sessions. In the earlier study at this plant (Makinia 2006), similar measurements were carried out (Figure 2). The estimated ratio of biodegradable to non-biodegradable particulate (and colloidal) organic fractions varied in the range of 1.8–2.5 to fit the waste activated sludge (WAS) production (Drewnowski &
Makinia 2011). As a consequence, the ratios of \(S_0/(S_0 + X_3)\) at the ‘Wschod’ WWTP (0.30–0.56) fitted well into a typical range of 0.5–0.5 (Sahlstedt et al. 2005). Furthermore, Pagilla et al. (2008) reported results of the COD distribution in the primary effluents of the plant based on the filtration of different pore size filters. The dominant fraction originating from particulate organic compounds (>1.2 \(\mu\)m) constituted 67\% of COD at the ‘Wschod’ WWTP.

The effects of precipitation on COD removal were investigated by Makinia et al. (2012). The three samples of SWW from the ‘Wschod’ WWTP were kept under anaerobic conditions to observe the release/uptake of soluble organic compounds (SCOD\(_{ini}\)) from the C–F precipitated solids (XCOD\(_{ini}\)). During the initial 2–3 days, the production of SCOD was clearly observed and described by the following equation:

\[
SCOD = SCOD_{ini} + XCOD_{ini} (1 - e^{-kt})
\]  

(1)

where the value \(k = 0.6–0.82\) [\(d^{-1}\)] was experimentally determined, using distribution functions, considering that SCOD was released from the precipitated solids of SWW. According to this study, the ratio of particulate and colloidal COD (XCOD) to VSS increased from 1.87–2.48 [g COD/g] (raw wastewater) to 2.65–2.80 [g COD/g] (SWW), due to sedimentation in the primary clarifiers. This indicates that a VSS fraction with a low COD/VSS ratio, such as particulate carbohydrates (Puig et al. 2010), was removed in the primary clarifiers. From a practical point of view, it should be noted that the conventional chemical precipitation with ferric chloride (FeCl\(_3\)) has similar effects to the method of Mamais et al. (1993). The rationale for the Mamais C–F method is based on the fact that \(S_0\) consists of simple molecules such as volatile fatty acids and low molecular weight carbohydrates that pass through the cell membrane and are metabolized immediately. Hu et al. (2002) indeed confirmed that the COD quantified with this method corresponded closely with the low (<1 kDa) molecular weight fraction. Grady et al. (1999) noted that for domestic wastewater, the C–F method gives results that correlate well with the conventional OUR tests. In a full-scale WWTP using FeCl\(_3\) to precipitate SWW, Xu & Hultman (1996) found no difference in COD determined in the samples of SWW both untreated and treated with ZnSO\(_4\). Discrepancies between the physical–chemical method and respirometric measurements may especially be observed for samples with a high content of industrial wastewater (Carrette et al. 2001). Ginestet et al. (2002) characterized samples of raw wastewater originating from seven French WWTPs. Respirometric measurements were carried out with samples of the raw, settled and ‘coagulated’ (i.e. settled and precipitated with FeCl\(_3\)) wastewater. The latter group predominantly consisted of the readily hydrolysable fraction (37–90\%), whereas the readily biodegradable and inert fractions accounted for 2–27\% and 2–47\% of soluble COD, respectively. Even though colloidal particles, which normally pass the filter, are removed before filtration, the filtered COD is equal to the truly soluble COD rather than only to the \(S_0\) (Xu & Hultman 1996). In addition, truly soluble COD is the sum of three fractions: inert, readily biodegradable and rapidly hydrolysable; especially the last form, which passes through the membrane filtrate, may have an impact on respiration rates for the same concentration of SCOD (Sollfrank & Gujer 1991; Orhon & Colgkor 1997).

The impact of colloidal and particulate (\(X_3\)) organic compounds on OUR

Table 2 contains ranges of the heterotrophic growth yield (\(Y_{H}\)) coefficient and OURs estimated during the batch tests (low or high \(S_0/X_3\) ratio) with the settled wastewater without pretreatment (SWW) and after coagulation–floculation (SWW C–F) at the ‘Wschod’ WWTP.

‘Low \(S_0/X_3\)’ OUR tests

Batch test results of OURs, with low \(S_0/X_3\) ratio, provided a good indication of the biological activity (Figures 3(a) and 3(b)). In the experiments with the SWW, the observed OURs were associated with the utilization of soluble (\(S_0\)), colloidal and particulate (\(X_3\)) organic compounds. The OUR values in R1 varied within the ranges 15.4–30.2 and 29.2–49.8 [mg O\(_2\)/g VSS·h] during the winter
summer sessions, respectively. When the pretreated samples of wastewater after C–F were used in the corresponding experiments (R2), the observed OURs were associated with the utilization of SS and the remaining colloidal organic fraction (part of XS). Consequently, the R2 values of OURmax were lower in comparison to the parallel tests (R1) with the SWW without pretreatment. The OUR values in the R2 varied within the ranges 8.9–24.9 [mg O₂/(g VSS · h)] (winter session) and 19.8–35.8 [mg O₂/(g VSS · h)] (summer session). Moreover, the initial (first hour of feed period) OUR values during the experiment with SWW without pretreatment (R1) were on average even 30% higher in comparison to wastewater sampled after C–F (R2).

The values reported by Ali et al. (1985) for the OUR laboratory-scale experiments with mixed liquor of wastewater and biomass were up to 50 [mg O₂/(g VSS · h)]. Comparable results were also reported by Jorgensen et al. (1992) for the OUR experiments with municipal wastewater.

### Table 2

<table>
<thead>
<tr>
<th>Process Unit</th>
<th>Winter session (13.5–13.9 °C)</th>
<th>Summer session (19.1–20.1 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SWW</td>
<td>SWW C–F</td>
</tr>
<tr>
<td>Low So/Xo OUR tests</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OURmax [mg O₂/gVSS · h]</td>
<td>15.4–30.2</td>
<td>8.9–24.9</td>
</tr>
<tr>
<td>OURendog. [mg O₂/gVSS · h]</td>
<td>2.8–11.4</td>
<td>2.2–7.8</td>
</tr>
<tr>
<td>YH [g COD/g COD]</td>
<td>0.59–0.71</td>
<td>0.62–0.70</td>
</tr>
<tr>
<td>High So/Xo OUR tests</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OURmax [mg O₂/gVSS · h]</td>
<td>67.0–76.6</td>
<td>21.7–51.5</td>
</tr>
<tr>
<td>OURendog. [mg O₂/gVSS · h]</td>
<td>6.5–7.9</td>
<td>3.2–6.4</td>
</tr>
<tr>
<td>YH [g COD/g COD]</td>
<td>0.58–0.64</td>
<td>0.64–0.82</td>
</tr>
</tbody>
</table>

### Figure 3

Examples of the OUR tests with low So/Xo ratio during the summer study session T = 20.0 °C: (a) MLVSS = 1.24–1.40 [kg/m³]; (b) MLVSS = 1.50–1.69 [kg/m³] with the SWW without pretreatment and after coagulation–floculation at the ‘Wschod’ WWTP. (MLVSS = mixed liquor volatile suspended solids.)
and activated sludge. In that study, the OURs associated with utilization of the $S_S$ and $X_S$ varied within the range of 20 and 22–53 [mg O_2/(g VSS · h)], respectively, from a pilot-scale and full-scale plant. For comparison, Choi & Daehwan (2001) found that particulate COD contributed to the increase of total OUR (including nitrification) by approximately 5.5% when the particulate COD constituted 65% of total COD (50% of the particulate fraction was estimated to be biodegradable). The soluble solution was made of filtered nightsoil, while the particulate solution was made of SWW and nightsoil.

‘High $S_0/X_0$’ OUR tests

In contrast, batch tests with high $S_0/X_0$ ratio showed that OUR differences mostly depend on heterotrophic biomass concentration. In the first period of the batch test with SWW without pretreatment (R1), oxygen respiration increased due to unlimited heterotrophic growth on $S_S$ and $X_S$. At this level of oxygen respiration, growth on $S_S$ is dominated by released forms of biodegradable substrates (transformation of $X_S$ to $S_S$) according to the hydrolysis process of $X_S$. In the case of the later sample, after C–F, OUR values gradually decrease to endogenous respiration level, because of limiting concentrations of biodegradable substrates (only $S_S$). After 4 h of the batch test, when the $S_S$ was depleted, OUR values suddenly decreased to the endogenous respiration baseline in both batch tests with SWW without pretreatment (total COD) and the later sample after C–F (soluble COD).

The removal of colloidal and particulate fractions by C–F, in comparison to the parallel sample with SWW without pretreatment, resulted (similar to OUR tests with low $S_0/X_0$ ratio) in reduced process rates (Figure 4). The OUR_{max} values varied in R1 within the ranges 67.0–76.6 (winter) and 61.8–88.0 [mg O_2/(g VSS · h)] (summer), whereas in R2 the values were lower and varied within the ranges 21.7–51.5 (winter) and 36.8–53.8 [mg O_2/(g VSS · h)] (summer) at ‘Wschod’ WWTP. Variable results were also obtained during earlier studies conducted by Sozen (1995) and Ubay Cokgor (1997) for OUR experiments with municipal wastewater associated with utilization of $S_S$, where the OUR values varied within the range of 23–86 [g O_2/m^3]. Interesting behaviour in this study was observed, when the pretreated samples of SWW (R2) were used, in the experiments with high $S_0/X_0$ ratio. The reported OURs (during the initial first hour of feed period) were higher in R2 (Figure 4(a)) only if the initial COD concentration was high (sufficient $S_S$). When the soluble COD was low from the very beginning of the test, the observed OURs were reduced in comparison to the parallel sample with SWW.

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Figure 4 | Examples of the OURs tests with high $S_0/X_0$ ratio during the winter study session $T = 13.5–14^\circ\text{C}$: (a) MLVSS = 0.06–0.51 kg/m^3; (b) MLVSS = 0.29–0.32 kg/m^3 with the SWW without pretreatment and after coagulation–floculation at the ‘Wschod’ WWTP.
without pretreatment (Figure 4(b)). For comparison with another study, Kristensen et al. (1992) demonstrated that hydrolysis of primary sludge can produce a broad range of $S_0$. The authors, based on the OURs observation with hydrolysate (a liquid phase of the anaerobically hydrolysed primary sludge) as a carbon source, concluded that oxygen respiration was typically 10–20% higher compared to the OUR tests with acetate.

### YH coefficient in OUR tests

Simultaneous measurement of COD and OUR during batch tests allowed estimation of the heterotrophic growth yield ($Y_{H}$) coefficient according to Equation (2). The $Y_{H}$ determined in both samples of SWW during respirometric experiments in the winter and summer study sessions at ‘Wschod’ WWTP are summarized in Table 2. The values of $Y_{H}$ estimated during OUR tests with low $S_0/X_0$ ratio for the SWW without pretreatment and after C–F remained in a relatively narrow range, i.e. 0.59–0.72 and 0.56–0.70 [g cell COD/g COD], respectively. By comparison, the $Y_{H}$ obtained during OUR tests with high $S_0/X_0$ ratio were 0.58 and 0.64 (SWW) and 0.63–0.82 [g cell COD/g COD] (SWW C–F).

$$Y_{H} = \frac{\text{COD}_{\text{deg}}}{\text{COD}_{\text{deg}}} - \int (\text{OUR}_{\text{tot}} (t) - \text{OUR}_{\text{end}} (t)) dt$$

(2)

Both OUR batch tests with low and high $S_0/X_0$ ratio showed that the removal of COD by degradation was stoichiometric to oxygen usage. The $Y_{H}$ from this study was comparable with results presented in the literature. The typical values of $Y_{H}$ for municipal wastewater, reported by Henze et al. (1987), were within the range of 0.46–0.69 [g cell COD/g COD]. Moreover, estimated by the method of Sollfrank & Gujer (1991) and further by Orhon et al. (1996), the values of $Y_{H}$ = 0.63–0.64 for domestic wastewater were confirmed. Hence, the default value of $Y_{H}$ = 0.63 [g cell COD/g COD], used in ASM2 and ASM2d, agreed with a typical range reported in the earlier study. The same value was assumed as the ASM3 default for heterotrophic growth on cell internal storage products ($X_{STO}$) but Rieger et al. (2001) increased the $Y_{H}$ yield to 0.8 [g cell COD/g COD] in ASM3P. For comparison, Dircks et al. (1999) proved that the difference in the $Y_{H}$ coefficient could also indeed result from the type of substrate. The reported $Y_{H}$ values for the activated sludge from two studied Danish WWTPs were 0.71–0.72 and 0.66–0.67 [g cell COD/g COD] for acetate and ethanol, respectively.

### CONCLUSIONS

From this study, the following conclusions can be derived:

- A novel procedure, based on the standard batch tests with parallel (SWW and after C–F) samples was adapted for evaluation of the impact of $X_0$ on the OURs in activated sludge systems.
- The removal of colloidal and particulate fractions ($X_0$) by the C–F method resulted in reduced process rates. The major discrepancy in the rate reductions (over 300% referred to the OUR$_{\text{max}}$) was observed during the OUR test with high $S_0/X_0$ ratio.
- The simultaneous measurement of COD and OUR during batch respirometric experiments allowed estimation of the heterotrophic growth yield ($Y_{H}$) coefficient. An estimated $Y_{H}$ parameter showed that the removal of COD by degradation was stoichiometric to oxygen usage, reflecting the consumption of biodegradable substrates and heterotrophic growth of biomass.
- Evaluation of the OUR profile could be recommended as a method for $X_0$ hydrolysis estimation. In addition to the experimental observations, the wastewater characteristic (soluble, colloidal and particulate fractions) and loading of biodegradable organic compounds could affect performance of OURs as well as several mechanisms during the process: value of temperature and/or DO, etc.
- The impact of $X_0$ is important in the overall energy balance of WWTPs in terms of balancing the nutrient removal efficiency in the bioreactor and biogas production in the digester. The results of such comparative study can provide a comprehensive database for calibration and evaluation of dynamic models of the hydrolysis process.

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REFERENCES


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