Biodegradability of wastewater – a method for COD-fractionation

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Abstract Characterization of wastewater for simulation of in-sewer transformations can be carried out by interpretation of oxygen uptake rate measurements in combination with a conceptual model of the microbial transformations involved. This interpretation can be done by iterative procedures by solving the differential equations constituting the model or by the application of a more “manual” method – the latter being the topic of this paper. Examples where different wastewaters are characterized illustrate the method.

Keywords Biodegradability; OUR; wastewater

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_H$</td>
<td>maximum specific growth rate for $X_{Bw}$</td>
<td>$d^{-1}$</td>
</tr>
<tr>
<td>$k_{h,fast}$</td>
<td>hydrolysis rate constant for $X_{S,fast}$</td>
<td>$d^{-1}$</td>
</tr>
<tr>
<td>$k_{h,slow}$</td>
<td>hydrolysis rate constant for $X_{S,slow}$</td>
<td>$d^{-1}$</td>
</tr>
<tr>
<td>$K_S$</td>
<td>saturation constant for $S$ (g COD m$^{-3}$)</td>
<td></td>
</tr>
<tr>
<td>$K_{X,fast}$</td>
<td>saturation constant for $X_{S,fast}$ (g COD g COD$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td>$K_{X,slow}$</td>
<td>saturation constant for $X_{S,slow}$ (g COD g COD$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td>$q_m$</td>
<td>maintenance energy rate constant for $X_{Bw}$ (d$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td>$S_S$</td>
<td>readily biodegradable substrate (g COD m$^{-3}$)</td>
<td></td>
</tr>
<tr>
<td>$S_O$</td>
<td>dissolved oxygen (g O$_2$ m$^{-3}$)</td>
<td></td>
</tr>
<tr>
<td>$X_{Bw}$</td>
<td>heterotrophic active biomass (g COD m$^{-3}$)</td>
<td></td>
</tr>
<tr>
<td>$X_{S,fast}$</td>
<td>fast hydrolysable substrate (g COD m$^{-3}$)</td>
<td></td>
</tr>
<tr>
<td>$X_{S,slow}$</td>
<td>slowly hydrolysable substrate (g COD m$^{-3}$)</td>
<td></td>
</tr>
<tr>
<td>$Y_H$</td>
<td>yield constant for $X_{Bw}$ (g COD g COD$^{-1}$)</td>
<td></td>
</tr>
</tbody>
</table>

Introduction

Crude parameters like biological oxygen demand (BOD), chemical oxygen demand (COD) or volatile solids (VS) are traditionally used to characterize organic matter in wastewater. These parameters determine the quantity of the organic matter present. COD and VS are measures of the total concentration of organic matter and BOD indicates the total amount of biodegradable organic matter. However, neither method gives detailed information on the composition of the fractions of biodegradable organic matter. Some information on the wastewater biodegradability can be gained comparing different measures, e.g. BOD and COD where a high ratio of BOD to COD shows that the wastewater is relatively biodegradable whereas a low ratio indicates that the wastewater is more slowly biodegraded.

In many cases such rather qualitative information on the wastewater organic matter and its microbial properties is not sufficient and a more detailed characterization is needed. This is for instance the case when optimizing sewer performance to meet wastewater treatment requirements – both when dealing with biological nutrient removal and with mechanical treatment. When addressing in-sewer treatment, detailed information on the wastewater biodegradability is crucial. Also when assessing impacts on receiving waters...
from combined sewer overflows (CSO), a more detailed knowledge on wastewater composition with respect to the biodegradability of the organic matter is needed.

A detailed characterization of the wastewater organic matter can be achieved, dividing the total COD into fractions with different microbiological properties (Henze, 1992). One of the COD fractions is the active agent in the microbial transformations: the heterotrophic microbial biomass. Other fractions are substrate for this biomass. Some of the substrate is readily biodegradable and some is more slowly biodegradable, i.e. it must be hydrolyzed before it can be utilized by the heterotrophic biomass. Another part of the organic matter is not biodegradable at all; i.e. it is inert.

Such fractionation of wastewater organic matter is routinely applied in the simulation of the microbial processes occurring in activated sludge of wastewater treatment plants (Henze, 2000). However, its application for simulation of in-sewer wastewater transformations of organic matter is a rather new approach (Bjerre et al., 1998). The methodology has been brought to other applications; e.g. the characterization of sewer sediment biodegradability (Vollertsen and Hvitved-Jacobsen, 1998). Furthermore, it has been suggested to apply the method for simulation of urban runoff impacts on receiving water (Ashley et al., 1999) and simulation of odor formation in sewage systems (Hvitved-Jacobsen and Vollertsen, 2000).

Sewers, treatment plants and receiving waters are interacting and it is therefore crucial that the concepts used to describe microbial transformations in the three systems are commensurable. Ideally the concepts should be identical. However, some very simplified descriptions of the microbial transformations are applied – simplifications which ignore many well known and well established biological facts (Nielsen et al., 1997; Vollertsen et al., 2001). This is not done out of ignorance, but because an operational model for the simulation of such a complex microbial system has to be rather simple to succeed for practical applications.

A complex model, taking many different processes into account, needs the calibration of a large number of model parameters and initial concentrations of model components. Naturally, such variables vary from case to case (else they would not be variables) and hence need to be determined for every model application. Unfortunately, this is often an impossible task when facing practical engineering problems. Therefore, only the most important processes may be taken into account. However, which processes are most important depends on the microbial environment to be simulated. E.g. in activated sludge systems the concentration of heterotrophic biomass is high and the readily biodegradable substrate concentration is low. In sewers, on the other hand, readily biodegradable substrate is typically plentiful and the heterotrophic biomass concentration is comparatively low. Hence, the biomass in activated sludge plants is organic substrate limited while this is seldom the case in sewers (Hvitved-Jacobsen et al., 1998). Consequently the importance of the microbial processes differs in these two systems, leading to somewhat different simplifications of the microbial transformations involved.

The model concept for in-sewer wastewater transformations

A concept for the simulation of wastewater transformation processes occurring in sewers has been developed and validated under laboratory and field conditions (Figure 1). It differs from the concept applied for simulation of activated sludge processes by omitting decay of biomass because this process is of minor importance during wastewater transport in sewers. Instead a maintenance energy requirement of the heterotrophic biomass is introduced to account for experimental evidence on a substantial non-growth related oxygen uptake. Furthermore, hydrolysable substrate has been subdivided to account for experimental evidence. Inert soluble and inert particulate organic matter are omitted because...
processes related to these fractions are of minor importance due to the relatively short residence times in sewer systems. To establish the COD mass balance these fractions are lumped into the slowly hydrolysable substrate fraction. For details on the model concept see Hvitved-Jacobsen et al. (1998) and Vollertsen and Hvitved-Jacobsen (1999).

The overall number of model parameters and model components is about the same for the simulation of wastewater transformations in treatment plants and wastewater transformations in sewers. The differences between the models are solely due to differences in the relative importance of the microbial processes involved in the biodegradation. For the determination of all model parameters and model components, experimental procedures have been developed. Most of these procedures are based on explicit methods (Vollertsen and Hvitved-Jacobsen, 1999).

Identification of model components and model parameters

Ideally all the components involved in the microbial transformation of wastewater organic matter should be determined explicitly at any time (Figure 1). However, no direct, continuous method for the determination of any of the COD components exists. Instead, determination of the heterotrophic biomass respiration rate in terms of the oxygen uptake rate (OUR) is settled for. Two examples of wastewater OUR measurements are shown in Figure 2. By measuring OUR, one model component – the consumed dissolved oxygen ($S_O$) – is explicitly determined. By means of the concept (Figure 1), an OUR measurement allows the initial concentrations of heterotrophic biomass ($X_{Bw}$) and readily biodegradable substrate ($S_{S}$) to be calculated when growth is not limited by substrate. The two hydrolysable substrate fractions ($X_{S,fast}$ and $X_{S,slow}$) can be found when the availability of readily biodegradable substrate is limiting the microbial transformations (Vollertsen and Hvitved-Jacobsen, 1999).

The use of OUR (respirometry) to characterize wastewater is also known from activated sludge. Here activated sludge is added to wastewater and the OUR is measured, either in

![Figure 1](https://iwaponline.com/wst/article-pdf/45/3/25/425170/25.pdf)

**Figure 1** The concept for transformation of organic matter in wastewater under sewer conditions

![Figure 2](https://iwaponline.com/wst/article-pdf/45/3/25/425170/25.pdf)

**Figure 2** Two examples of wastewater OUR measurements. In [A] exponential growth takes place as $S_{S}$ is present, in [B] the exponential growth is due to $X_{S,fast}$.
continuously fed reactors or in batch reactors (Spanjers et al., 1998). However, for the purpose of characterizing in-sewer transformations, seeding with activated sludge would make it problematic to distinguish between e.g. biomass and substrate limitations. Hence OUR is measured on unseeded batches of wastewater (Bjerre et al., 1995).

Interpretation of an OUR measurement using the concept can be done by simulation of the measurement made (Vollertsen and Hvitved-Jacobsen, 1998). The concept can be written as 5 differential equations – one for $X_{Bw}$, $S_S$, $X_{S,fast}$, $X_{S,slow}$ and $S_O$. For example for $S_O$, Figure 1 shows that two processes influence this component: growth of the biomass and maintenance energy requirement of the biomass. Equation 1 is the corresponding differential equation establishing the mass balance in $S_O$. Equations for all components and processes are shown in Table 1, using the “matrix” notation known from activated sludge modeling.

\[ \text{OUR}(t) = \frac{\partial (S_O)}{\partial t} = \frac{1}{Y_H} \frac{Y_H}{\mu_H} \frac{S_S}{K_S + S_S} X_{Bw} + q_m X_{Bw} \] (1)

When certain simplifying assumptions are made, an OUR measurement can be interpreted without solving the coupled differential equations. This method and the required assumptions are discussed in the following paragraphs. By this approach, all model components and one model parameter can be found. To find the other parameters, numerical simulation and supplementary experiments must be made (Vollertsen and Hvitved-Jacobsen, 1999).

**Determination of the model components**

When determining the model components and the model parameters, some ($X_{Bw}$, $S_S$, $\mu_H$) are obtained from the first few hours of an OUR measurement. Readily biodegradable organic substrate is often naturally present in wastewater and in this case organic substrate does not limit the heterotrophic growth during the first part of an OUR experiment. Other components are obtained during substrate limited conditions later in the measurement ($X_{S,fast}$, $X_{S,slow}$).

**Determination of $X_{Bw}$ and $\mu_H$**

It can be seen from Table 1 that OUR must increase exponentially when the substrate is not limiting the growth because the term $S_S/(K_S + S_S)$ then converges towards unity and the growth equation consequently simplifies to a 1’ order rate equation in $X_{Bw}$. However, the observation of an exponential increase in OUR is not conclusive evidence that growth is taking place without substrate limitation. Hydrolysable substrate ($X_S$) may also cause exponential growth at a rate equal to or smaller than the maximum specific growth rate of $X_{Bw}$ ($\mu_H$). When $X_{S,fast}$ in $X_{Bw}$ is much greater than the saturation constant for hydrolysis ($K_X$), the two rate equations for hydrolysis (Table 1) also reduce to 1’ order in $X_{Bw}$ and the biomass will likewise grow exponentially. However, it is mostly straightforward to distinguish between $S_S$ and $X_S$ causing an exponential OUR increase because the transition from exponential growth to substrate limited growth occurs significantly faster when the growth is due to $S_S$ than when it is due to $X_{S,fast}$. This is a combined effect of the hydrolysis rate equation switching from 1’ order in $X_{Bw}$ to 1’ order in $X_{S,fast}$ when $X_{S,fast}$ becomes depleted and the ratio of $K_X$ to $X_{S,fast}/X_{Bw}$ typically found in wastewater (Vollertsen and Hvitved-Jacobsen, in preparation). In Figure 2, graph A shows wastewater where $S_S$ is initially present and graph B shows an exponential growth on fast hydrolysable substrate. Note in the first case the sharp decrease in OUR after 4–5 hours and in the second case the much slower decrease.

The initial concentration of $X_{Bw}$ can be found explicitly from the initial OUR value when substrate does not limit the growth. Isolation of $X_{Bw}$ from the differential equation
Table 1 Model concept, process kinetics and stoichiometry for microbial wastewater transformations under DO non-limited conditions, cf. Figure 1. Symbols are explained in the list of nomenclature.

<table>
<thead>
<tr>
<th>Component j</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Process rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Aerobic growth</td>
<td>$1$</td>
<td>$\frac{1}{Y_H}$</td>
<td>$1$</td>
<td>$\frac{1}{Y_H}$</td>
<td>$\mu$</td>
<td>$\frac{S_S}{K_S + S_S} X_{Bw}$</td>
</tr>
<tr>
<td>2 Maintenance energy requirement</td>
<td>$-1$</td>
<td>$-1^*$</td>
<td>$1$</td>
<td>$q_m X_{Bw}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Hydrolysis, fast</td>
<td>$1$</td>
<td>$-1$</td>
<td>$k_{B,fast} \frac{X_{B,fast}}{X_{Bw}} K_{B,fast} + X_{B,fast} X_{Bw}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Hydrolysis, slow</td>
<td>$-1$</td>
<td>$k_{B,slow} \frac{X_{B,slow}}{X_{Bw}} K_{B,slow} + X_{B,slow} X_{Bw}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* If $S_S$ is not present in sufficient concentration $X_{Bw}$ is used to supply the remaining COD (endogenous respiration).

When using Equation 2 to find the initial concentration of $X_{Bw}$, $OUR(t_0)$ should be found from Equation 3 and not from the measurement itself because different phenomena may make the measured value uncertain. I.e. temperature equalization or oxidation of inorganic compounds ($H_2S$, $Fe^{2+}$) may cause “false” oxygen uptake rates in the beginning of an OUR experiment (Vollertsen and Hvitved-Jacobsen, 1998).

If $S_S$ is absent but OUR still increases at a rate close to typical maximum rates (Figure 2A), $X_{Bw}$ can be estimated from the OUR at time zero. $\mu_H$ must then be estimated from the initial OUR increase according to Equation 3 even though this increase is not exponential. This underestimates $\mu_H$ and hence overestimates $X_{Bw}$, but typically not largely so. If none or only little $S_S$ and $X_{S,fast}$ is present – i.e. the OUR is more or less unchanged with time (Figure 5F) – $X_{Bw}$ can be estimated assuming that all the substrate is consumed for maintenance (Equation 4).
Determination of $S_S$

The heterotrophic yield relates the growth of biomass to the substrate consumed (Equation 5) and Equation 6 is the mass balance for the growth process. Combination of these two equations results in Equation 7, converting between the oxygen consumed for biomass growth and the equivalent $S_S$ consumed.

\[ Y_H = \frac{X_{Bw}}{S_{S,\text{growth}}} \]  \hspace{2cm} (5)

\[ X_{Bw} + S_{S,\text{growth}} + \left( S_{O,\text{growth}} \right) = 0 \]  \hspace{2cm} (6)

\[ S_{S,\text{growth}} = \frac{S_{O,\text{growth}}}{1 - Y_H} \]  \hspace{2cm} (7)

However, $S_S$ and $S_O$ are also used for maintenance energy requirement of the biomass (Equation 8). Under substrate non-limited conditions, the required substrate for maintenance is small compared to the consumed substrate for growth. Typically the $S_S$ produced by hydrolysis is sufficient to fulfil the maintenance energy requirement of the biomass under substrate non-limited conditions. For the data obtained by Vollertsen and Hvitved-Jacobsen (in preparation) it can be deduced that in the beginning of an OUR experiment, hydrolysis contributes with several times the amount of $S_S$ required for biomass maintenance.

\[ S_{S,\text{maint}} = S_{O,\text{maint}} \]  \hspace{2cm} (8)

The area beneath an OUR curve consequently is a measure of the consumed $S_S$. Some $S_S$ was initially present and some was produced by hydrolysis during the experiment. To distinguish between these fractions without detailed simulation of the OUR, the simplifying assumption that hydrolysis is a 1' order process in $X_{Bw}$ must be made. This is a reasonable assumption in the beginning of an OUR experiment as $X_{S,\text{fast}}/X_{Bw}$ typically is 2–10 times larger than $K_{X,\text{fast}}$ and $X_{S,\text{slow}}/X_{Bw}$ typically is 25–150 times larger than $K_{X,\text{slow}}$ (Vollertsen and Hvitved-Jacobsen, in preparation). When both hydrolysis, biomass maintenance and biomass growth are of 1’ order in $X_{Bw}$, the $S_S$ produced by hydrolysis will correspond to a constant fraction of the total OUR. Furthermore, because $K_S$ is small – Vollertsen and Hvitved-Jacobsen (1999) found an average $K_S$ value of 0.7 g COD m$^{-3}$ – the transition to substrate-limited growth (Figure 3) is sufficiently fast that biomass can be viewed as constant throughout this transition. When all the initially present $S_S$ is consumed, the observed OUR is solely caused by a consumption of $S_S$ produced by hydrolysis and hence the fraction of OUR due to $S_S$ produced by hydrolysis is known at this time; i.e. $b_2/(a_2+b_2)$ in Figure 3. As previously mentioned this fraction can be assumed constant, and hence the OUR due to $S_S$ produced by hydrolysis is known at any time, i.e. $a_1/b_1 = a_2/b_2$. The curve separating the two areas in Figure 3 is an exponential curve but in most cases a straight line will give an acceptable approximation. Therefore, the oxygen consumed ( $S_O$) due to the consumption of initially present $S_S$ can be found as the area A in Figure 3 and the initial amount of $S_S$ ( $S_S$) can be calculated using Equation 7.
Determination of \( X_{S,\text{fast}} \) and \( X_{S,\text{slow}} \)

Some few hours after start of an OUR experiment on wastewater, growth of the heterotrophic biomass becomes limited by the availability of organic substrate. Substrate is present but the biomass cannot utilize it directly – it has to undergo hydrolysis into \( S_S \) before it can be taken up. If the rate with which \( S_S \) is produced by hydrolysis is higher than the \( S_S \) consumed for biomass maintenance, the biomass will continue to grow. Wastewater contains many different types of organic matter being hydrolyzed at different rates. Typically, a lumping of these into 2 fractions of hydrolysable substrates gives an adequate simplification for wastewater characterization purposes. The fractions can normally be identified after 1–2 days of OUR measurement at 20°C (Hvitved-Jacobsen and Vollertsen, 1998).

After \( X_{S,\text{fast}} \) has been consumed, only \( X_{S,\text{slow}} \) (and eventually endogenous respiration of \( X_{B_w} \)) will contribute to the OUR measured. Therefore, a change in the slope of the OUR curve to a semi-constant level can be seen where this shift takes place (Figure 4). Assuming that the hydrolysis rate of \( X_{S,\text{slow}} \) is of 1’ order in the biomass, the conclusion can be drawn that \( a_1/b_3 = a_4/b_3 \). I.e. the amount of oxygen taken up due to \( S_S \) produced by hydrolysis of \( X_{S,\text{slow}} \) is proportional to the biomass throughout the experiment (i.e. \( K_{X,\text{slow}} \ll X_{S,\text{slow}}/X_{B_w} \)). The line separating the oxygen uptake due to \( X_{S,\text{fast}} \) and the oxygen uptake due to \( X_{S,\text{slow}} \) (Figure 4) is not really a straight line, but can be approximated as such. The oxygen uptake due to consumption of \( S_S \) produced by hydrolysis of \( X_{S,\text{fast}} \) is hence the area B in Figure 4.

The conversion from \( X_S \) to the hydrolysis product (\( S_S \)) is straightforward, because one COD unit of \( X_S \) is hydrolyzed into one COD unit of \( S_S \) (Table 1). However, the conversion from \( S_S \) consumed to \( S_S \) consumed is not as readily performed. The reason is that hydrolysis of \( X_{S,\text{slow}} \) may be insufficient to supply the \( S_S \) necessary for the maintenance energy requirement of the biomass. Analyzing data from Vollertsen and Hvitved-Jacobsen (in preparation), it can be seen that the \( S_S \) produced from hydrolysis of \( X_{S,\text{slow}} \) typically can supply most of the \( S_S \) needed for maintenance – but not all. A fraction of the \( S_S \) produced by hydrolysis of \( X_{S,\text{fast}} \) must therefore be used for biomass maintenance and not for biomass growth. As Equation 8 is valid for the first process while Equation 7 is valid for the second process, the correct conversion lies somewhere in-between. Comparing the two equations, it is seen that the difference is not trivial when calculating the amount of \( X_{S,\text{fast}} \). However, as \( X_{S,\text{slow}} \) typically can supply the main part of the requirement for maintenance, it is for practical reasons suggested to use Equation 7 only. Hence Equation 9 should be used to convert from the measured oxygen uptake due to hydrolysis of \( X_{S,\text{fast}} \) to \( X_{S,\text{fast}} \).

\[
X_{S,\text{fast}} = S_{S,\text{growth}} = \frac{S_O}{Y_H}.
\] (9)

\[ \text{Figure 3} \quad \text{Determination of } S_S \text{ from an OUR curve} \]

\[ \text{Figure 4} \quad \text{Determination of } X_{S,\text{fast}} \text{ from an OUR curve} \]
The slowly hydrolysable substrate cannot be determined from the OUR measurement alone, partly because it does not become depleted in the experiment and partly because it includes inert organic matter. Instead $X_{S,\text{slow}}$ is determined from the mass balance in COD (Equation 10). Hereby both soluble and particulate inert organic matters are lumped into the fraction of slowly hydrolysable substrate.

$$X_{S,\text{slow}} = \frac{COD_{\text{total}}}{X_{B_w} + S^f + X_{S,\text{fast}}} \quad (10)$$

**Examples of wastewater characterization**

The shape of wastewater OURs do vary a lot, depending mainly on the presence of readily biodegradable substrate and fast hydrolysable substrate (Figure 5). To illustrate this and to illustrate the wastewater characterization method described, 6 samples of different – and random – origin and with different compositions are characterized (Table 2). For this characterization $Y_H = 0.70$, $q_m = 1.4$ (average values reported by Vollertsen and Hvitved-Jacobsen, 1999) were used to calculate the initial component concentrations.

**Conclusion**

OUR measurements are a versatile tool for characterization of the biodegradability of organic matter because they can be interpreted applying a simplified conceptual model of the microbial transformations taking place. The interpretation can be performed, simulating the measurements by solving the coupled differential equations constituting the model.

In this paper a method alternative to model simulation has been presented. Simplifying assumptions can in most cases be made, allowing a manual interpretation of the OUR measurement. When these assumptions are valid, oxygen uptake due to both readily biodegradable substrate and fast hydrolysable substrate can be identified on an OUR graph and converted to substrate concentrations. Furthermore, the biomass can be calculated from initial OUR values. The slowly hydrolysable substrate is found from the COD mass balance.

The presented method allows in most cases a simple and fast assessment of wastewater biodegradability in terms of the COD fractions needed for simulation of in-sewer
wastewater transformations. Addressing the impact of a sewer system on treatment plants, assessment of in-sewer transformations of the organic matter is crucial. E.g. when wastewater is to be treated mechanically, ideal wastewater contains much of its COD in a particulate form and the soluble part is poorly biodegradable. On the other hand, ideal wastewater for nutrient removal contains much readily biodegradable substrate and/or much fast hydrolysable substrate. Applying knowledge on in-sewer transformations, wastewater can be designed to meet the demands of the treatment process. The presented methodology allows a ready characterization of wastewaters for this purpose.

Acknowledgements
We wish to thank Maria do Céu de Sousa Teixeira de Almeida and Suhaimi Abdul Talib for kindly letting us use their measurements.

References

Table 2 Examples of OUR measurements on wastewater, cf. Figure 5

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\mu_H$ [d$^{-1}$]</th>
<th>$S_S$ [gCOD m$^{-3}$]</th>
<th>$X_{BS}$ [gCOD m$^{-3}$]</th>
<th>$X_{B,fast}$ [gCOD m$^{-3}$]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Portugal)</td>
<td>$\geq 5.0$</td>
<td>0</td>
<td>61</td>
<td>309</td>
<td>The exponential increase in OUR – being characteristic for initially present $S_S$ – is not seen in the two wastewaters. OUR increases fast, however, not exponentially. Furthermore, the fast decrease in OUR which is seen when initially present $S_S$ has been consumed is absent. Hence no, or only little, $S_S$ is present in these samples.</td>
</tr>
<tr>
<td>B (Malaysia)</td>
<td>$\geq 5.8$</td>
<td>0</td>
<td>34</td>
<td>95</td>
<td>A large amount of $S_S$ and $X_{B,fast}$ can clearly be distinguished and $\mu_H$ readily found. The shift from substrate non-limited growth to substrate-limited growth is very clear.</td>
</tr>
<tr>
<td>C (Germany)</td>
<td>8.3</td>
<td>83</td>
<td>20</td>
<td>119</td>
<td>2 or 3 fractions of $S_S$ seem to be present and $X_{B,fast}$ absent. Exponential increases occur during the first 12 hours, however, with different corresponding growth rates. $\mu_H$ is found from the first 4 hours.</td>
</tr>
<tr>
<td>D (Germany)</td>
<td>5.4</td>
<td>18</td>
<td>75</td>
<td>176</td>
<td>A small amount of $S_S$ is present – barely enough to determine $\mu_H$ – and a large amount of $X_{B,fast}$ is seen. Again it is straightforward to distinguish between the two fractions.</td>
</tr>
<tr>
<td>E (Denmark)</td>
<td>5.4</td>
<td>18</td>
<td>75</td>
<td>176</td>
<td>No $S_S$ and no $X_{B,fast}$ is present as the OUR shows no or only little increase. $X_{BS}$ is found from Equation 4 and $\mu_H$ cannot be found.</td>
</tr>
</tbody>
</table>


