Modelling the degradation of endogenous residue and 'unbiodegradable' influent organic suspended solids to predict sludge production

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ABSTRACT

Activated sludge models have assumed that a portion of organic solids in municipal wastewater influent is unbiodegradable. Also, it is assumed that solids from biomass decay cannot be degraded further. The paper evaluates these assumptions based on data from systems operating at higher than typical sludge retention times (SRTs), including membrane bioreactor systems with total solids retention (no intentional sludge wastage). Data from over 30 references and with SRTs of up to 400 d were analysed. A modified model that considers the possible degradation of the two components is proposed. First order degradation rates of approximately 0.007 d^{-1} for both components appear to improve sludge production estimates. Factors possibly influencing these degradation rates such as wastewater characteristics and bioavailability are discussed.

Key words | endogenous residue, long SRT, membrane bioreactor, modelling, sludge production, total solids retention

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INTRODUCTION

Prediction of sludge production is an important issue for wastewater treatment plant (WWTP) modelling, and it is considered a crucial step in calibration of activated sludge models (ASMs). In the theoretical framework of these models (ASM1, ASM2, ASM3) the mixed liquor suspended solids is composed mainly of active microorganisms (X_H), inactive/inert particulate organic matter (X_U) and inorganic matter (X_{Ig}) (Henze *et al.* 2000; symbols according to Corominas *et al.* 2010). Storage compounds are also considered in ASM2, ASM2d and ASM3, and slowly biodegradable organics are also present to a lesser extent. The inert organic matter (X_U) originates from the influent ($X_{U,Inf}$) and the accumulation of endogenous residue (X_E) from biomass decay. This concept was initially developed by Marais & Ekama (1976) and Dold *et al.* (1980) for conventional activated sludge processes operating at typical sludge retention times (SRTs), i.e. < 30 d. The terms 'inactive' or 'inert' organic matter are replaced in this paper by the more specific term 'unbiodegradable'.

Several articles deal with the operation of membrane bioreactors (MBRs) at very long SRTs and the concept of MBRs with 'total solids retention', i.e. nearly no solids wastage (Rosenberger *et al.* 2002; Laera *et al.* 2005; Lubello *et al.* 2009). In some of these studies authors reported a zero observed mixed liquor volatile suspended solids (MLVSS) production, suggesting that biomass (active and endogenous residue) production was equilibrated by

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biomass decay (or that influent substrate was completely oxidised for cell maintenance). If such systems were stable in terms of MLVSS concentration, it would imply that a significant degradation of $X_{\mathrm{U,Inf}}$ and X_{E} occurs. This concept is clearly still controversial, and in opposition to the actual ASM framework. Adaptation of ASM models for MBRs was recently reviewed and the need to include a slow 'hydrolysis' process was pointed out (Spérandio & Espinosa 2008; Fenu *et al.* 2010).

Recent research indicates that sludge production at long SRTs is slightly lower than expected based on models calibrated at conventional SRTs. Several studies point out a need to introduce the degradation of endogenous products (X_{E}) and influent 'unbiodegradable' particulate organics ($X_{\mathrm{U,Inf}}$) (Spérandio & Espinosa 2008; Lubello *et al.* 2009; Fenu *et al.* 2010; Ramdani *et al.* 2012). The objective of this article is to discuss these recent findings and to evaluate the predictions of a modified ASM with datasets obtained from MBRs operated over a large range of SRTs.

THEORETICAL BACKGROUND

Simulated sludge production in conventional activated sludge or MBRs depends *inter alia* on influent organic and inorganic loads and on some core model parameters (mainly Y_{H}, f_{XE} and b_{H}; Table 1). As SRT increases, the predicted mass of volatile solids in the system (and the observed sludge production) becomes dominated by the unbiodegradable particulate COD (chemical oxygen demand) components $X_{\mathrm{U,Inf}}$ and X_{E}.

The expression of sludge production yield (kg VSS/kg COD removed) at steady state based on conventional ASMs (ASM-based model with endogenous respiration concept) is:

$$Y_{\mathrm{OBS}} = \left((1-f_{\mathrm{XU}}-f_{\mathrm{SU}}).\left(\frac{Y_{\mathrm{H}}}{(1+b_{\mathrm{H}}.\mathrm{SRT})}\frac{1}{f_{\mathrm{cv,XH}}} + \frac{Y_{\mathrm{H}}.b_{\mathrm{H}}.f_{\mathrm{XE}}.\mathrm{SRT}}{(1+b_{\mathrm{H}}.\mathrm{SRT})}\frac{1}{f_{\mathrm{cv,XE}}}\right) + \frac{f_{\mathrm{XU}}}{f_{\mathrm{cv,XU,Inf}}}\right)/(1-f_{\mathrm{SU}}) \quad (1)$$

Parameters definition and typical values are given in Table 1. Equation (1) is developed for aerobic conditions and a single value for the Y_{H} coefficient is assumed. Considering different Y_{H} values depending on electron acceptor would be more accurate for systems with anaerobic and anoxic conditions.

Table 1 | Typical parameters values

Symbol	Parameter description	Value	Units
Y_{H}	Heteretrophic biomass yield (aerobic)	0.666	g COD/g COD
b_{H}	Decay rate of heterotrophic biomass	0.24	d^{-1}
b_{XE}	Degradation rate of endogenous particulate 'residue'	0.007	d^{-1}
b_{XU}	Degradation rate of influent particulate unbiodegradable organics	0.007	d^{-1}
f_{SU}	Soluble unbiodegradable organics fraction of wastewater COD	0.05[a]	g COD/g COD
f_{XU}	Particulate unbiodegradable organics fraction of wastewater COD	0.08–0.20[a]	g COD/g COD
f_{XE}	Endogenous fraction of biomass (endogenous respiration concept)	0.20	g COD/g COD
$f_{\mathrm{CV,XH}}$	Conversion factor for heterotrophic biomass	1.42	g COD/g VSS
$f_{\mathrm{CV,XU,Inf}}$	Conversion factor for influent unbiodegradable particulate COD	1.55[a]	g COD/g VSS
$f_{\mathrm{CV,XE}}$	Conversion factor for endogenous residue	1.55	g COD/g VSS

[a]Wastewater dependent.

In the case of synthetic soluble substrates, as $f_{\mathrm{XU}} = 0$ and $f_{\mathrm{SU}} = 0$, Equation (1) is simplified to:

$$Y_{\mathrm{OBS}} = \frac{Y_{\mathrm{H}}}{(1+b_{\mathrm{H}}.\mathrm{SRT})}\frac{1}{f_{\mathrm{cv,XH}}} + \frac{Y_{\mathrm{H}}.b_{\mathrm{H}}.f_{\mathrm{XE}}.\mathrm{SRT}}{(1+b_{\mathrm{H}}.\mathrm{SRT})}\frac{1}{f_{\mathrm{cv,XE}}} \quad (2)$$

If the degradation of endogenous residue is considered as a first order kinetic, the mass balance for X_{E} gives:

$$V\frac{\mathrm{d}X_{\mathrm{E}}}{\mathrm{d}t} = V.f_{\mathrm{XE}}.b_{\mathrm{H}}.X_{\mathrm{H}} - V.b_{\mathrm{XE}}.X_{\mathrm{E}} - PX_{\mathrm{E}} = 0 \quad (3)$$

where V is the reactor volume and PX_{E} is the wasted endogenous suspended solids.

Then Equation (1) becomes:

$$Y_{\mathrm{OBS}} = \left((1-f_{\mathrm{XU}}-f_{\mathrm{SU}}).\left(\frac{Y_{\mathrm{H}}}{(1+b_{\mathrm{H}}.\mathrm{SRT})}\frac{1}{f_{\mathrm{cv,XH}}} + \frac{Y_{\mathrm{H}}.b_{\mathrm{H}}.f_{\mathrm{XE}}.\mathrm{SRT}}{(1+b_{\mathrm{H}}.\mathrm{SRT})(1+b_{\mathrm{XE}}.\mathrm{SRT})}\frac{1}{f_{\mathrm{cv,XE}}}\right) + \frac{f_{\mathrm{XU}}}{f_{\mathrm{cv,XU,Inf}}}\right)/(1-f_{\mathrm{SU}}) \quad (4)$$

If the degradation of $X_{U,Inf}$ is introduced, also as a first order kinetics, the mass balance on $X_{U,Inf}$ is:

$$V\frac{dX_{U,Inf}}{dt} = Q.f_{XU}.T_{Inf,COD} - V.b_{XU,Inf}.X_{U,Inf} - PX_{U,Inf} = 0 \quad (5)$$

where $T_{Inf,COD}$ is the total influent COD concentration.

Consequently, the observed sludge production yield, considering the degradation of $X_{U,Inf}$ and X_E, is expressed (modified ASM model) as:

$$Y_{OBS} = \left((1-f_{XU}-f_{SU}).\left(\frac{Y_H}{(1+b_H.SRT)}\frac{1}{f_{cv,XH}} + \frac{Y_H.b_H.f_{XE}.SRT}{(1+b_H.SRT)(1+b_{XE}.SRT)}\frac{1}{f_{cv,XE}}\right) + \frac{f_{XU}}{(1+b_{XU,Inf}.SRT)}\frac{1}{f_{cv,XU,Inf}}\right)/(1-f_{SU}) \quad (6)$$

In this first order kinetic approach, it is implicitly assumed that both X_E and $X_{U,Inf}$ can eventually be degraded completely. However, there may be a portion that cannot be degraded at all.

RESULTS

Identifying degradation rate of X_E or $X_{U,Inf}$ in batch tests

The degradation rates of X_E or $X_{U,Inf}$ were estimated either during long-term digestion (anaerobic or aerobic) or in MBRs (Table 2). A first order kinetic reaction was proposed for these processes for the specific parameters b_{XE} or b_{XU}. It is considered essential to accurately evaluate the value of the 'core' parameters Y_H, f_{XE} and b_H in ASM models (Ramdani 2011).

Model-based evaluation of sludge yield measurements in MBR literature

Based on a literature review from 30 references covering the last 30 years (Table 3), the excess sludge production in MBRs was evaluated in terms of both model concepts: with or without the degradation of X_E and $X_{U,Inf}$ (Figure 1). Data are provided for MBRs treating both synthetic soluble substrate ($f_{XU} = 0$) and real wastewater (Figure 1(a) and 1(b), respectively). The x axis shows SRT and duration for MBRs operated with solids wastage and with total solids retention, respectively. For MBRs operated at SRTs longer than 50 d, the modified ASM model better predicted sludge production, using a mean degradation rate value of 0.007 d^{-1} for both b_{XE} and b_{XU}. This result is in agreement with the degradation rate for b_{XE} determined by Ramdani *et al.* (2012).

Obviously a significant variability is observed in the data from literature and this should not be considered as a definitive rate value. Variability can be related to the wastewater characteristics (or type of synthetic carbon source), the presence of anoxic and anaerobic conditions and the temperature variations in the case of full-scale data. Analysis of available data obtained at long SRT or total solids retention indicates that applying degradation rates for endogenous residue (b_{XE}) in the range 0.0035–0.017 d^{-1} may improve predictions of sludge production depending on the data (cross-flow filtration versus submerged membrane filtration; laboratory-scale versus full-scale systems). Higher degradation rates were obtained mostly from the cross-flow mode of operation, which could be explained by a higher shear stress resulting in some sludge disintegration.

The values of f_{XU} which give exactly the same sludge production yield with Equation (1) (ASM based) and Equation (6) (modified ASM) are shown in Figure 2. For example at an SRT of 20 d, the same Y_{OBS} is predicted with $f_{XU} = 0.16$ for the conventional model (Equation (6)) and with $f_{XU} = 0.20$ for the model which includes degradation of $X_{U,Inf}$ and X_E (Equation (6)). With the conventional model, f_{XU} should be reduced to less than 0.10 at an SRT of 60 d, and f_{XU} should tend theoretically towards zero at SRTs greater than 200 d in order to predict the same sludge production as by the modified model. In contrast, this last model, including the degradation of

Table 2 | Degradation rate constants estimated for X_E or $X_{U,Inf}$

Parameter	b_{XE}	b_{XE}	$b_{XE\,+}\,b_{XU}$	$b_{XE\,+}\,b_{XU}$
References	Ramdani *et al.* (2010)	Ramdani *et al.* (2012)	Lubello *et al.* (2009)	Jones *et al.* (2007)
Conditions	Batch, 35 °C	MBR, 20 °C	MBR, 20 °C	Batch, 35 °C
Aerobic	–	0.006–0.007 d^{-1}	0.012–0.014 d^{-1}	–
Aerobic/anaerobic	0.012 d^{-1}	–	–	–
Anaerobic	0.005 d^{-1}	–	–	0.0075 d^{-1}

Table 3 | Effect of influent type, MBR type and conditions, sludge utilisation rate (SUR) and SRT/duration on observed sludge production yield

		SUR	SRT*/ Duration**	Y_{OBS}		
Influent	**MBR type & conditions**	**g COD/ (g VSS · d)**	**d**	**g VSS/g COD**	**Authors**	**Country**
Synthetic soluble wastewater, with solids wastage*						
Acetate, corn starch, yeast extract	Submerged	9.670	0.25	0.414	Ng & Hermanowicz (2005)	USA
		6.070	0.5	0.329		
		5.220	0.5	0.383		
		1.430	2.5	0.280		
		0.790	5	0.253		
Glucose, peptone	Submerged	0.104	90	0.107	Bhatta *et al.* (2004)	Japan
		0.083	120	0.100		
		0.072	160	0.087		
Not detailed	Submerged	0.250	200	0.022	Hay *et al.* (2006)	Singapore
Meat extract, propionate, peptone, ethanol	Submerged	0.392	12	0.205	Spérandio *et al.* (2004)	France
Meat extract, propionate, tryptone	Submerged	0.333	12.5	0.240		
Meat extract, tryptone, ethanol	Submerged	0.245	20	0.204	Lesage *et al.* (2005)	France
		0.278	20	0.180		
		0.192	40	0.130		
Ethanol, methanol, acetate	Submerged	0.353	20	0.142	Mozo *et al.* (2011)	France
		0.322	20	0.155		
		0.418	16	0.150		
Synthetic complex	Crossflow	0.187	100	0.063	Chaize & Huyard (1991)	France
			100	0.070		
Ethanol, methanol, acetate	Crossflow	0.554	20	0.090	Mozo *et al.* (2011)	France
		0.536	20	0.093		
		0.724	10	0.138		
Synthetic soluble wastewater, total solids retention**						
Acetate	Submerged	0.091	233	0.047	Heran *et al.* (2008)	France
		0.137	160	0.042		
		0.062	393	0.041		
Acetate, peptone, yeast extract, paper	Submerged		133	0.050	Chiemchaisri *et al.* (1992)	Japan
			330	0.048		
Glucose , peptone	Submerged	0.060	200	0.033	Bhatta *et al.* (2004)	Japan
		0.100	200	0.020		
		0.043	200	0.047		
Domestic wastewater, with solids wastage*						
Raw wastewater + acetate (20%)	Submerged, AN/AX/OX	0.171	20	0.292	du Toit *et al.* (2007)	South Africa
Screened wastewater	Submerged	0.109	50	0.183	Buisson *et al.* (1998)	France
Screened wastewater	Submerged, AX/OX	0.123	56.7	0.143	Coté *et al.* (1998)	France
		0.114	62.3	0.140		
		0.100	67.5	0.148		

(*Continued*)

Table 3 | Continued

Influent	MBR type & conditions	SUR g COD/(g VSS · d)	SRT*/ Duration** d	Y_{OBS} g VSS/g COD	Authors	Country
Screened wastewater	Submerged, AX/OX	0.175	23	0.248	Al-Halbouni *et al.* (2008)	Germany
		0.112	40	0.222		
Screened wastewater	Submerged, AX/OX	0.0797	60	0.209	Delrue *et al.* (2010)	France
Screened wastewater	Submerged, AX/OX Full scale	0.117	35	0.243	de Wever *et al.* (2008)	Belgium
Screened wastewater	Submerged, AX/OX	0.303	15	0.22	Jimenez *et al.* (2010)	France
		0.166	40	0.15		
Screened wastewater	Crossflow	0.1	100	0.10	Chaize & Huyard (1991)	France
Screened wastewater	Crossflow	0.242	20	0.206	Urbain *et al.* (1998)	France
		0.243	20	0.205		
Screened wastewater	Crossflow	0.201	30	0.165	Wen *et al.* (1999)	China
		0.239	15	0.278		
		0.53	5	0.377		
Domestic wastewater, total solids retention**						
Domestic primary effluent	Submerged		150	0.106	Rosenberger *et al.* (2002)	Germany
Domestic primary effluent	Submerged		120	0.120	Pollice *et al.* (2004)	Italy
Primary effluent, peptone, apple juice	Submerged		300	0.021	Wagner and Rosenwinkel (2000)	Germany

Note: AN: anaerobic; AX: anoxic; OX: aerobic. *SRT is indicated for studies with solids wastage. **Duration is indicated for studies with full solids retention.

$X_{U,Inf}$ and X_E, allows the prediction of the Y_{OBS} over a large range of SRTs with a constant f_{XU} value. This example shows that the conventional ASM-based model requires an undesirable adjustment to the parameter f_{XU} as a function of the SRT in order to obtain a good prediction of the sludge production yield over a large range of SRTs.

DISCUSSION

Sludge production measured in systems operated at very long SRTs or in long-term digestion tests could be predicted by modifying ASMs to include the degradation of $X_{U,Inf}$ (b_{XU}) and of X_E (b_{XE}). The fundamental mechanisms underlying this degradation and its kinetics (especially for $X_{U,Inf}$) are still under review. The value of 0.007 d^{-1} appears to be a good estimate for b_{XE} at 20 °C under aerobic conditions. The factors influencing these degradation rates are not yet fully understood. Both the physical accessibility and the chemical nature of these materials should be considered as well as their bioavailability. Hydrolysis of particles is, for example, controlled by extracellular enzymes and is a surface-limited process that depends on substrate availability and aggregate size (Dimock & Morgenroth 2006). For these reasons it can be expected that increasing mass transfer by high mixing or provoking physical disaggregation by mechanical or hydrodynamic constraints should both lead to higher hydrolysis rates. It seems realistic to think that processes that can destabilise the chemical bonds between bio-aggregates can also increase the hydrolysis rate of particulate organic matter. Conversely, coagulation with multivalent ions (iron, aluminium, calcium and magnesium) is known to modify the accessibility of extracellular polymeric substances, influencing the digestibility of sludge in aerobic and anaerobic conditions (Park *et al.* 2006).

Whereas recent works allow the estimation of the degradation rate of endogenous compounds, less investigated and more complex is the determination of degradation rates for influent solids which were modelled as 'inerts' until now ($X_{U,Inf}$). The degradation depends both on their chemical properties (Sophonsiri & Morgenroth 2004) and their size (Dimock & Morgenroth 2006). Based on respirometric

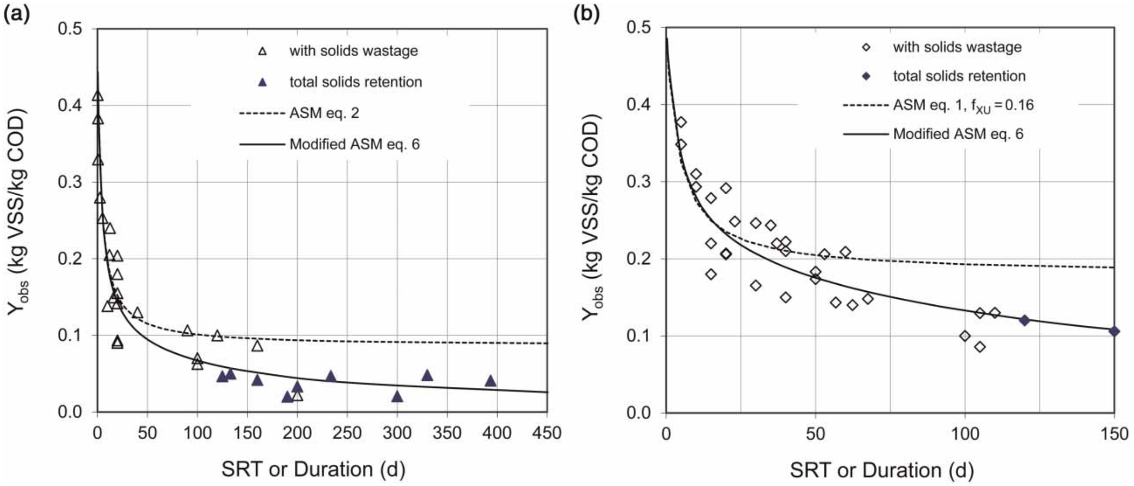

Figure 1 | Observed sludge production (Y_{obs}) for the ASM (Equations (1) and (2)) and the modified ASM (including degradation of $X_{U,Inf}$ and X_E; Equation (6); with $b_{XE} = b_{XU} = 0.007\ d^{-1}$). (a) MBR fed with synthetic soluble substrate, (b) MBR treating real wastewater.

tests (long term), Ginestet *et al.* (2002) found that the hydrolysis rate of a fraction of settleable solids (mostly the cellulosic fraction) can be simulated with a hydrolysis rate of 0.2 to 0.6 d^{-1}, which is a relatively low value compared to those used in conventional ASM models, but a much higher value than those estimated for 'unbiodegradable' compounds ($X_{U,Inf}$ and X_E). It seems reasonable to think that some organic solids in the influent have a very low hydrolysis rate, but more work would be necessary to estimate this kinetic rate. In the absence of such information, a similar hydrolysis rate, for X_E and $X_{U,Inf}$ can be used when dealing with systems working at very long sludge age as this assumption seems to give acceptable predictions (Figure 1).

The experimental determination of b_{XE} and b_{XU} values could be performed by specifically tailored long-term continuous or batch tests, with both synthetic sludges ($X_{U,Inf} = 0$) and real sludges (known f_{XU}), respectively, by fitting the simulated suspended solids and oxygen uptake rate to measured data. A similar experiment was completed for the determination of b_{XE} by Ramdani *et al.* (2012). The determination of b_{XU} is, however, more complex, requiring the determination of the feed f_{XU} value (often obtained by model calibration for sludge production) and a stable feed wastewater composition during a long-term experiment.

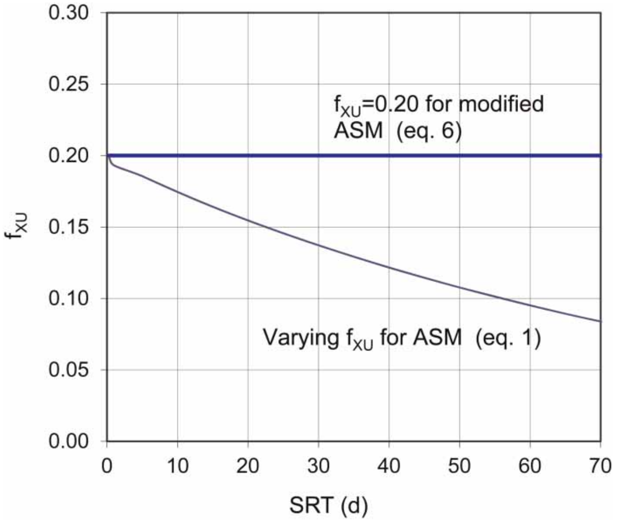

Figure 2 | f_{XU} values for a given sludge production yield with Equation (1) (conventional ASM model) and Equation (6) (with degradation of X_E and $X_{U,Inf}$). b_{XE} and b_{XU} were fixed at 0.007 d^{-1}.

CONCLUSIONS

Based on a literature review of MBRs treating synthetic or real wastewater, assuming an average degradation rate value of 0.007 d^{-1} for both, X_E or $X_{U,Inf}$ was found to improve the estimation of sludge production yields measured with MBRs operated at SRTs from 1 to 400 d. This result is in accordance with the estimation of degradation rate of endogenous residue from long-term batch experiments.

Including a degradation rate for components that traditionally were considered unbiodegradable (X_E and $X_{U,Inf}$) may require a change to some wastewater fractionation parameters and/or model kinetic and stoichiometric parameters. Finally the use of a modified ASM should allow the prediction of sludge production over a large range of SRTs with a constant value for f_{XU}. This modification should improve modelling of different technologies that aim to reduce sludge production, e.g. extended sludge aeration in MBRs, activated sludge processes with parallel sludge disintegration, oxidation or hypoxic digestion.

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