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Biodegradability of wastewater and activated sludge organics in anaerobic digestion

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ABSTRACT

The investigation provides experimental evidence that the unbiodegradable particulate organics fractions of primary sludge and waste activated sludge calculated from activated sludge models remain essentially unbiodegradable in anaerobic digestion. This was tested by feeding the waste activated sludge (WAS) from three different laboratory activated sludge (AS) systems to three separate anaerobic digesters (AD). Two of the AS systems were Modified Ludzack – Ettinger (MLE) nitrification-denitrification (ND) systems and the third was a membrane University of Cape Town (UCT) ND and enhanced biological P removal system. One of the MLE systems and the UCT system were fed the same real settled wastewater. The other MLE system was fed raw wastewater which was made by adding a measured constant flux (gCOD/d) of macerated primary sludge (PS) to the real settled wastewater. This PS was also fed to a fourth AD and a blend of PS and WAS from settled wastewater MLE system was fed to a fifth AD. The five ADs were each operated at five different sludge ages (10–60d). From the measured performance results of the AS systems, the unbiodegradable particulate organic (UPO) COD fractions of the raw and settled wastewaters, the PS and the WAS from the three AS systems were calculated with AS models. These AS model based UPO fractions of the PS and WAS were compared with the UPO fractions calculated from the performance results of the ADs fed these sludges. For the PS, the UPO fraction calculated from the AS and AD models matched closely, i.e. 0.30 and 0.31. Provided the UPO of heterotrophic (OHO, f_{E_OHO}) and phosphorus accumulating (PAO, f_{E_PAO}) biomass were accepted to be those associated with the death regeneration model of organism "decay", the UPO of the WAS calculated from the AS and AD models also matched well - if the steady state AS model $f_{E\_OHO} = 0.20$ and $f_{E\_PAO} = 0.25$ values were used, then the UPO fraction of the WAS calculated from the AS models deviated significantly from those calculated with the AD models. Therefore in plant wide wastewater treatment models the characterization of PS and WAS as defined by the AS models can be applied without modification in AD models. The observed rate limiting hydrolysis/acidogenesis rates of the sludges are listed.

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List of abbreviations

AD	Anaerobic digestion
ADM1	Anaerobic digestion models No 1
AS	Activated sludge
ASM1, 2, 2d	Activated sludge models No 1, 2 and 2d
BPO	Biodegradable particulate organics
BSM2	Benchmark simulation model No 2
BSO	Biodegradable soluble organics
COD	Chemical oxygen demand
d	Day
DSVI	Diluted sludge volume index
EBPR	Enhanced biological phosphorus removal
F	Filtered
F-BSO	Fermentable biodegradable soluble organics
FSA	Free and saline ammonia
g	gram
ISS	Inorganic suspended solids
l	Litre
m	Metre
MLE	Modified Ludzack-Ettinger system
N	Nitrogen
ND	Nitrification-denitrification
OHO	Ordinary heterotrophic organism
OUR	Oxygen utilization rate
P	Phosphorus
OP	Ortho-phosphate
PAO	Phosphorus accumulating organisms
PP	Polyphosphate
PS	Primary sludge
pH	Negative log of the hydrogen ion activity
SRT	Solids retention time (or sludge age)
TKN	Total Kjeldahl nitrogen
TP	Total phosphorus
TSS	Total suspended solids
UCT	University of Cape Town
UF	Unfiltered
UPO	Unbiodegradable particulate organics
USO	Unbiodegradable soluble organics
VFA	Volatile fatty acids
VSS	Volatile suspended solids
WAS	Waste activated sludge
WRC	Water Research Commission
WW	Wastewater
WWTP	Wastewater treatment plant

List of symbols[1]

b, /d	general parameter for endogenous respiration rate
E, –	Proportion of influent COD flux (gCOD/d) exiting system as sludge production (gCOD/d)
f_E, –	general parameter for unbiodegradable fraction of biomass
f_{COD_VSS}, gCOD/gVSS	COD content of organics (COD/VSS ratio, f_{cv})
f_{OHO_VSS}, gVSS/gVSS	OHO/VSS ratio of activated sludge ($=X_{OHO}/X_{VSS}$, f_{av})
f_{xE_OHO}, –	OHO unbiodegradable fraction associated with endogenous respiration in steady state ND AS model (=0.20, f_{EH})
f'_{xE_OHO}, –	OHO unbiodegradable fraction associated with death regeneration in dynamic ASM1 (=0.08, f'_{EH})
f_{xE_PAO}, –	PAO unbiodegradable fraction associated with endogenous respiration in steady state NDEBPR AS model (=0.25, f_{EG})
f'_{xE_PAO}, –	PAO unbiodegradable fraction when assigned the same value as OHOs associated with death regeneration (=0.08, f'_{EG})
f_{P_VSS}, gP/gVSS	Phosphorus content of particulate organics or biomass (f_p)
$f_{xU,CODInf}$, gCOD/gCOD	fraction of influent total COD that is unbiodegradable and particulate ($f_{S'up}$)
$f_{SU,CODInf}$, gCOD/gCOD	fraction of influent total COD that is unbiodegradable and soluble ($f_{S'us}$)
k_h, /d	Specific hydrolysis/acidogenesis rate of BPO in AD
k_H, gCOD/(l.d)	First order specific hydrolysis/acidogenesis rate of BPO in AD
k_m, gCOD/gCOD/d	Maximum BPO hydrolysis/acidogenesis rate in AD in Monod kinetics in AD
k_M, gCOD/gCOD/d	Maximum BPO hydrolysis/acidogenesis rate in AD in saturation kinetics in AD
K_s, gCOD/l	Half saturation concentration for BPO hydrolysis/acidogenesis in Monod kinetics in AD
K_S, gCOD/l	Half saturation concentration for BPO hydrolysis/acidogenesis in saturation kinetics in AD
r_{hyd}, gCOD/(l.d)	Volumetric BPO hydrolysis rate in AD
$X_{B,Eff}$, mgCOD/l	effluent biodegradable particulate COD concentration (S_{bpe})
$X_{B,Inf}$, mgCOD/l	influent biodegradable particulate COD concentration (S_{bpi})
$S_{B,Inf}$, mgCOD/l	influent biodegradable soluble COD concentration (S_{bsi})
$X_{U,Eff}$, mgCOD/l	effluent unbiodegradable particulate COD concentration (S_{upe})

1. Introduction

In plant wide modelling, a question that arises is “do organics that are unbiodegradable in the activated sludge (AS) system, namely, the unbiodegradable particulate organics (UPO, $X_{U,Inf}$)

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[1] As recommended by Corominas et al. (2010) with the UCT equivalent given in brackets for easy cross reference to the papers on the AS and AD steady state models in the old units.

$X_{U,Inf}$, mgCOD/l	influent unbiodegradable particulate COD concentration (S_{upi})
$S_{U,Inf}$, mgCOD/l	influent unbiodegradable soluble COD concentration (S_{usi})
$COD_{T,Eff}$, mgCOD/l	effluent total COD concentration (S_{te})
$COD_{T,Inf}$, mgCOD/l	influent total COD concentration (S_{ti})
X_{AFO}, mgCOD/l	Acid forming organism (AFO) concentration in AD (Z_{AD})
X_{OHO}, mgCOD/l	Ordinary heterotrophic organism (OHO) concentration (Z_{BH})
$X_{OHO,VSS}$, mgVSS/l	Ordinary heterotrophic organism (OHO) concentration (X_{BH})
$X_{U,E,OHO}$, mgCOD/l	OHO endogenous residue concentration (Z_{EH})
$X_{U,E,OHO,VSS}$, mgVSS/l	OHO endogenous residue concentration (X_{EH})
X_{PAO}, mgCOD/l	Phosphorus accumulating organism (PAO) concentration (Z_{BG})
$X_{PAO,VSS}$, mgVSS/l	Phosphorus accumulating organism (PAO) concentration (X_{BG})
$X_{U,E,PAO}$, mgCOD/l	PAO endogenous residue concentration (Z_{EG})
$X_{U,E,PAO,VSS}$, mgVSS/l	PAO endogenous residue concentration (X_{EG})
$X_{U,Reac}$, mgCOD/l	Unbiodegradable particulate COD concentration originating from the influent in the reactor (Z_I)
$X_{U,Reac,VSS}$, mgVSS/l	Unbiodegradable particulate VSS concentration originating from the influent in the reactor (X_I)
X_{VSS}, mgCOD/l	volatile solids concentration in COD units (Z_v)
$X_{VSS,VSS}$, mgVSS/l	volatile solids concentration in VSS units (X_v)
Y, gCOD/gCOD	biomass yield coefficient
μ, –	micrometre (10^{-6} m)

from the influent wastewater and endogenous residue ($X_{U,E}$) of the biomass, remain unbiodegradable in the anaerobic digester (AD)?". This question has been asked for a long time. Gossett and Belser (1982) fed waste activated sludge (WAS) grown on synthetic wastewater to AD systems. While they concluded that the endogenous residue of the ordinary heterotrophic organisms (OHO) remained unbiodegradable in the AD, their value determined for the endogenous residue fraction of the OHOs ($f_{E\_OHO} = 0.37$) differed significantly from that used in AS models for real wastewater, i.e. $f_{E\_OHO} = 0.20$ in endogenous respiration based steady state models, or equivalently, $f'_{E\_OHO} = 0.08$ in death-regeneration based dynamic models. van Haandel et al. (1998) grew AS on real domestic wastewater in a 2 d retention time aerated lagoon and decreased its OHO active fraction with respect to VSS (f_{OHO_VSS}) by aerobic digestion at different retention times before feeding it to ADs. They concluded from an empirical graphical procedure that about 15% of the OHO endogenous residue was degraded in AD. Ekama et al. (2006a,b) evaluated the Van Haandel data and a limited data set of their own with the mass balanced steady state AD model of Sötemann et al. (2005) and concluded that the unbiodegradable particulate organics (UPO) from the influent wastewater ($X_{U,Inf}$) and the OHO endogenous residue ($X_{U,E,OHO}$) remain unbiodegradable in the AD. Based on this experimental evidence, it was accepted in benchmark simulation model no 2 (BSM2, Jeppsson et al., 2006) and the steady state plant wide model of Ekama (2009), that the organics that are unbiodegradable in the AS system remain unbiodegradable in AD. However, an experimental investigation with real wastewater that examines this in a comprehensive and integrated plant wide set-up appears not to have been done yet.

2. Objectives

In the development of plant wide wastewater treatment plant (WWTP) models, considerations for including phosphorus (P) have commenced, e.g. linking ASM2 or ASM2d to ADM1 (Jeppsson et al., 2013). This opens a range of challenging issues in wastewater treatment plant (WWTP) modelling recently summarized by Vanrolleghem et al. (2014), e.g. upgrading ADM1 from two (aqueous-gas) to three phases (aqueous-gas-solid) to model mineral precipitation in the AD and elsewhere in the WWTP – this not only requires a comprehensive evaluation of ADM1 but also of the modelling of the physico-chemical phenomena associated with mineral precipitation (Batstone et al., 2012; Tait et al., 2012).

To investigate mineral precipitation in AD, a plant wide investigation with real wastewater was undertaken by Ikumi et al. (2011), which also provided the data to revisit the issue of the biodegradability of wastewater and AS organics. This paper describes this plant wide experimental set-up and focusses on the biodegradability of PS and AS organics in AD. The results of including P and mineral precipitation in AD will be presented in subsequent papers.

3. Methods and materials

3.1. *Plant wide experimental system layout and operation*

The experimental layout comprised three laboratory AS systems and five ADs (Fig 1). Two of the AS systems were Modified Ludzack – Ettinger (MLE) nitrification-denitrification (ND) systems and the third was a membrane University of Cape Town (UCT) ND and enhanced biological P removal (EBPR) system. One of the MLE systems (MLE1) and the UCT system were fed the same real screened (1 mm mesh) settled wastewater, which was collected from the Mitchells Plain WWTP (Cape Town, South Africa) in 1.2 m^3 batches. The other MLE system (MLE2) was fed raw wastewater which was made by adding a measured constant flux (7.2 gCOD/d) of macerated primary sludge (PS) to the collected settled wastewater. The waste activated sludge

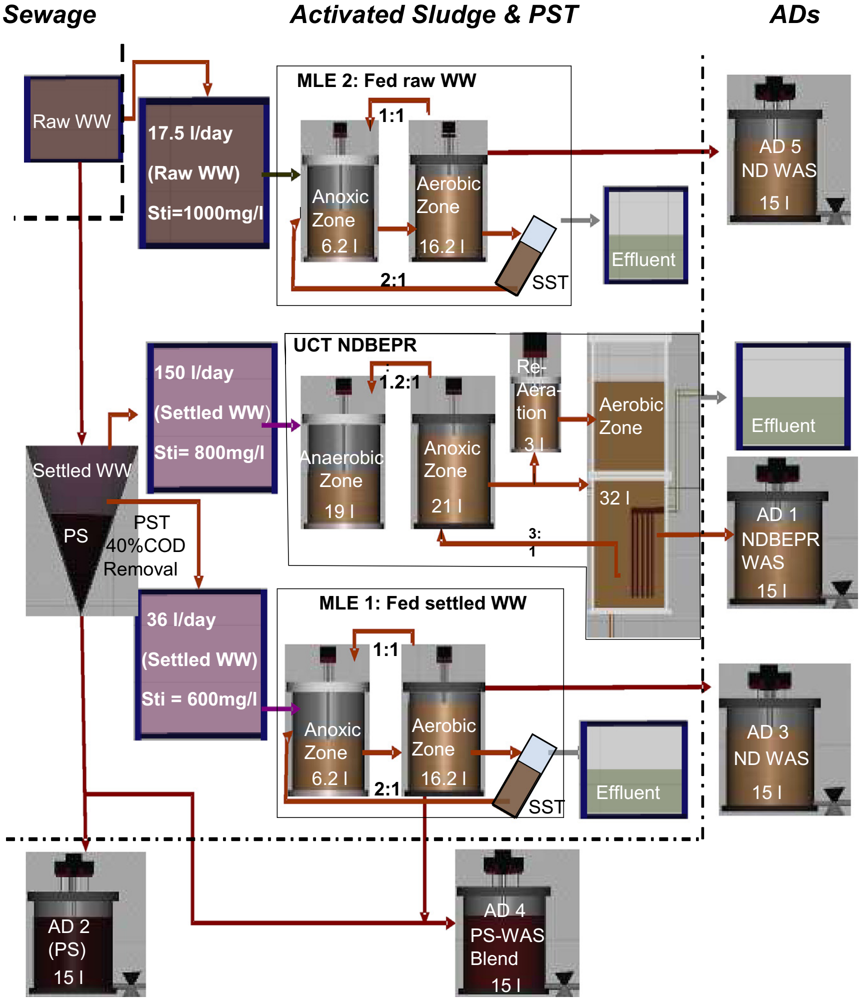

Fig. 1 – Experimental set-up for the investigation.

(WAS) from the MLE1, MLE2 and UCT systems was fed to AD3, AD5 and AD1 respectively. The same PS used to make the raw wastewater was fed to AD2 and a blend of this PS and WAS from MLE1 was fed to AD4.

The design and operating parameters of the AS systems are given in Table 1. To increase the P removal in the UCT system, 200 mgCOD/l acetate and 40 mgP/l of potassium dihydrogen phosphate (KH_2PO_4) were dosed to its settled wastewater feed. For each AD1 to AD5, there was one large (AD1L to AD5L, 20 l) and one small (AD1S to AD5S, 5 l) digester. The five large ADs were operated at 4 different sludge ages during the investigation, viz. 10, 18, 25 and 40 d, and the five small ADs only at 60 d. The small ADs were operated in parallel with the large ones so that they could reach steady state while the large ADs were tested.

3.2. *Control and monitoring of activated sludge (AS) systems*

The three AS systems were operated with hydraulic control of sludge age by withdrawing the required volume of mixed liquor (including samples) directly from the aerobic reactor to establish 10 d sludge age in all three systems (Table 1). This waste activated sludge (WAS) was retained for feeding to the ADs (and for the UCT system WAS, also to anoxic-aerobic digesters, which will be presented in subsequent papers). No attempt was made to control the AS systems' aerobic reactor TSS concentrations, which adopted their own value in response to the established sludge age and feed wastewater fluxes and characteristics (Ekama, 2010). Every second day, the three systems were monitored by measuring the parameters listed in Table 2 and the recycle flow rates checked.

Each 1.2 m^3 wastewater (WW) batch lasted 2–3 weeks, which was accepted to represent a steady-state period. This was necessary because the TKN/COD ratio of some consecutive wastewater batches were significantly different. The results measured every second day over a wastewater batch were averaged (after analysis for and rejection of outliers). These steady-state averages were used to assess the performance of the systems and the following AS system characteristics were calculated: System COD, N, P, Mg, K and Ca flux balances; influent unbiodegradable soluble (USO, $f_{SU,CODInf}$) and particulate (UPO, $f_{xU,CODInf}$) COD fractions with the method of Ekama and Wentzel (1999) (explained below); aerobic reactor suspended solids (mixed liquor) VSS/TSS, COD/VSS, TKN/VSS and TP/VSS mass ratios; nitrate and filtered TP

Table 1 – Design and operating parameters and target feed COD concentrations of the three AS systems.

Parameter	UCT system	MLE1 system	MLE2 system
WW type	Settled WW	Settled WW	Raw WW
Sludge age (d)	10.4	10	10
Influent COD (mg/l)	600 + 200[a]	600	600 + 400[b]
Influent flow (l/d)	150	36	18
Waste flow (l/d) (from aerobic reactor)	5.74	2.24	2.24
Volume (l)/Mass fractions: Anaerobic	19; 0.133	–	–
Volume (l)/Mass fractions: Anoxic	21/0.275	6.2/0.28	6.2/0.28
Volume (l)/Mass fractions: Aerobic	35/0.592	16.2/0.72	16.2/0.72
Recycle ratios: a (aerobic to anoxic)	3.40	2.0	2.0
Recycle ratios: s (from settling tank)	–	1.0	1.0
Recycle ratios: r (anoxic to anaerobic)	1.15	–	–
HRT – nominal/actual (h): Anaerobic	3.04/1.41	–	–
HRT – nominal/actual (h): Anoxic	3.36/0.61	4.13/1.03	8.26/2.06
HRT – nominal/actual (h): Aerobic	5.6/1.27	10.8/2.7	21.6/5.4

[a] Dosed 200 mgCOD/l sodium acetate.
[b] Added per day 400 mgCOD/l (i.e. 7.24 gCOD) primary sludge.

flux changes across each reactor, and the influent (readily) biodegradable soluble organics (BSO) COD concentration (S_{bsi}) from the difference between the 0.45 μm membrane filtered influent and effluent COD concentrations.

3.3. *Operation of anaerobic digester (AD) systems*

The five large ADs were 20 l clear Perspex continuously stirred tank reactors sealed with upper and lower lids bolted together with eight vertical stainless steel rods around the external periphery to ensure a gas-tight seal and provide structural support (Fig 2). Gas volume was measured by a gas volume counter directly connected to the ADs. The five small ADs were 5 l conical glass flasks placed on magnetic stirrers and sealed with rubber stoppers to leave minimal headspace. Gas volume was measured by downward displacement of water and the inverted floating plastic measuring cylinder was fitted with a vent port sealed with a screw clamp. For the large and small ADs, gas was collected into 5 l Tedlar gas bags. Because PS hydrolyses faster than WAS, the AD2L fed PS and AD4L fed the PS-WAS blend were fed more frequently (three or two times daily) at the short sludge ages to avoid high VFA concentrations and low pH after feeding. At each sludge age change, a period of 2–3 sludge ages was allowed to elapse before experimental tests and measurements were performed on the ADs.

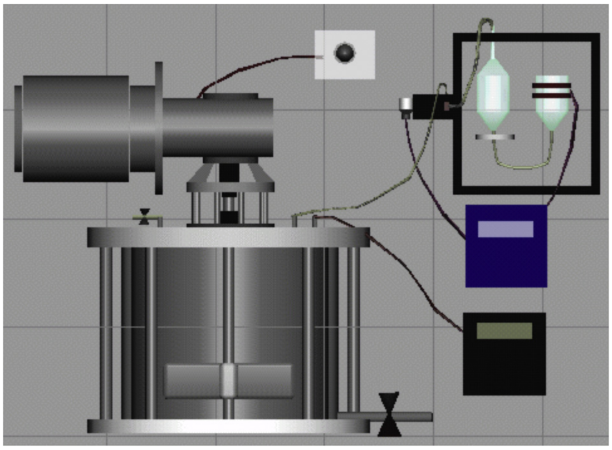

Fig. 2 – Schematic diagram of the large anaerobic digesters.

3.4. *Anaerobic digester feed preparation and monitoring*

AD1L&S were fed UCT system WAS taken directly from the aerobic reactor at a concentration of ~9 gCOD/l without thickening. The daily feed volume was changed to establish the required sludge age on AD1L and AD1S. So for AD1, the shorter the sludge age, the higher the gCOD/d feed was applied. Because the two MLE systems did not produce a high flux of WAS, the WAS from these systems was thickened to a higher concentration to decrease the daily feed volume with increase in AD sludge age and maintained a constant daily

Table 2 – Activated sludge system sampling position and parameter measurement.

Test	COD	TKN	VFA	FSA	NO_3	NO_2	TP	OP	Me^+	Alk	TSS	VSS	OUR	DSVI	pH
Influent	F; UF	UF	UF	F			UF; F	F	UF; F	UF					
Anaerobic					F	F	F				UF	UF			
Anoxic					F	F	F				UF	UF			
Aerobic	UF	UF			F	F	UF		UF; F		UF	UF	D	D	D
Final effluent	F	F; UF	F	F	F	F	F; UF	F		F					

F = 0.45 μm filtered; UF = Unfiltered samples; D = Direct measurement taken.
COD (Chemical Oxygen Demand), TKN (Total Kjeldahl Nitrogen), FSA (Free and Saline Ammonia), TP (Total Phosphorus), OP (Ortho-P), TSS (total suspended solids), VSS (volatile suspended solids) according to Standard Methods (1998). NO_3 (Nitrate) and NO_2 (Nitrite) by Technicon Auto-Analyser Industrial Method 33.68 and 35.67W; Me^+ (metals – Mg, K, Ca) by acid digestion of unfiltered (UF) and filtered (F) samples followed by atomic adsorption analysis. DSVI (Diluted Sludge Volume Index) according to Ekama and Marais (1984); OUR (Oxygen Utilization Rate) measured directly in aerobic reactor according to Randall et al. (1991). VFA (volatile fatty acids) and H_2CO_3 alkalinity with the 5 point titration of Moosbrugger et al. (1992).

Table 3 – Sludge flows, COD fluxes and feed COD concentrations fed to AD1(L&S) to AD5(L&S) during the five AD test periods of the investigation.

Digester			Test period	1	2	3	4	5
			Period dates	1 Feb–8 Apr	9 Apr–4 Jul	1 Feb–12 Jun	5 Jul–28 Aug	28 Aug–2 Nov
			Period duration (days)	68	87	133	55	66
			WW batches used	13–14	15–16	16–17	18–19	20–21
			AD sludge age	18 d	40 d	60 d*	25 d	10 d
	Sludge type	Vol.		l/d	l/d	l/d	l/d	l/d
			Flow (l/d)	0.89	0.40	0.083	0.64	1.6
AD1 L	NDBEPR	16 l	Flux (gCOD/d)	8.94	4.05	0.87	6.14	14.98
AD1 S	WAS	5 l	Conc (gCOD/l)	10.06	10.13	10.42	9.59	9.36
			Flow (l/d)	0.67	0.30	0.083	0.48	1.2
AD2 l		12 l	Flux (gCOD/d)	5.37	5.61	2.37	4.28	6.82
AD2 S	PS	5 l	Conc (gCOD/l)	8.05	18.71	28.43	8.91	5.68
			Flow (l/d)	0.67	0.30	0.083	0.48	1.2
AD3 L	MLE1 (fed settled WW)	12 l	Flux (gCOD/d)	2.43	2.42	0.98	2.47	3.20
AD3 S	WAS	5 l	Conc (gCOD/l)	3.65	8.05	11.71	5.15	2.67
			Flow (l/d)	0.67	0.3	0.083	0.48	1.2
AD4 L	PS & MLE1	12 l	Flux (gCOD/d)	7.77	8.01	3.46	6.61	10.13
AD4 S	WAS	5 l	Conc (gCOD/l)	11.65	26.70	41.46	13.77	8.44
			Flow (l/d)	0.83	0.38	0.083	0.6	1.5
AD5 L	MLE2 (fed raw WW)	15 l	Flux (gCOD/d)	5.60	6.63	2.06	4.93	4.55
AD5 S	WAS	5 l	Conc (gCOD/l)	6.72	17.69	24.75	8.21	3.03

* 60 d ADs were operated as the small 5 l conical flasks.

COD feed flux (gCOD/d) throughout the investigation. Table 3 lists the sludge flows, fluxes and feed concentrations of the different sludges fed to the ADs at their different sludge ages during the experimental investigation.

After the ADs were run for 2–3 sludge ages to reach steady state, they were tested according to the sampling and analysis schedule shown in Table 4. The AD steady state periods were selected to align with the 1.2 m^3 wastewater (WW) batches fed to the AS systems. The daily results measured on the ADs during these WW batches were averaged to give the AD performance. The results from the AS systems measured over the same and one previous WW batches were averaged to give the AS system performance.

3.5. *Experimental programme duration and data evaluation*

Over the first six months of the investigation (WW Batches 1–9), experimental system operation and monitoring procedures were refined and improved to achieve good mass balances over the systems. The data acquired from 1st Feb., 2008 to 2nd Nov., 2008 (WW batches 10 to 21, 276 days) achieved good mass balances and so were reliable to meet the research objectives. The dates, duration, WW batches and AD sludge ages of the five AD test periods are given in Table 3. The average results measured on the AS and AD systems over WW batches 13 to 21 are given in Tables 5 and 6. In the interests of brevity, only the AD concentrations relevant to this paper are given – all the results from the investigation are given by Ikumi et al. (2011).

In operating the AS systems, the factors important for the investigation were that (1) no EBPR occurred in the MLE systems so the biodegradability of their WAS organics in the ADs could be compared with that of the UCT system with EBPR and (2) the EBPR in the UCT system was not affected by nitrate recycle to the anaerobic reactor. Both these objectives were met at all times in the investigation. The low P removals in the MLE1 and MLE2 (Table 5) confirm that no EBPR took place in these systems and the phosphorus was utilized for sludge production only – no polyphosphate (PP). In contrast, the very high P removal of the UCT system

Table 4 – Anaerobic digester (AD) sampling position and parameter measurement.

Test	COD	TKN	VFA	FSA	Gas Vol	Gas %CO_2	TP	OP	Me^+	Alk	TSS	VSS	pH
Influent	F; UF	F; UF	UF	F			F; UF	F	F; UF	UF	UF	UF	
Reactor					D	D			F				D
Effluent	F; UF	F; F	F	F			F; UF	F	F	F	UF	UF	

F = 0.45 μm filtered; UF = Unfiltered samples; D = Direct measurement taken when access port was opened to feed the AD (usually once daily); COD (Chemical Oxygen Demand), TKN (Total Kjeldahl Nitrogen), FSA (Free and Saline Ammonia), TP (Total Phosphorus), OP (Ortho-P), TSS (total suspended solids), VSS (volatile suspended solids) were determined according to Standard Methods (1998); VFA (volatile fatty acids) and Alk (H_2CO_3 alkalinity) with the 5 point titration of Moosbrugger et al. (1992); gas was collected in 5L Tedlar gas bags and CO_2 and CH_4 composition analysed by gas chromatograph; Me^+ (metals – Mg, K, Ca) by acid digestion of unfiltered (UF) and filtered (F) samples followed by atomic adsorption (AA) analysis.

Table 5 – Average results measured in the three AS systems over WW batches 13 to 21.

Parameter	UCT system	MLE1 system	MLE2 system
WW type	Settled WW	Settled WW	Raw WW
Sludge age (d)	10.4	10	10
Influent COD (mg/l)	787[a] ± 29	619 ± 29	1047[b] ± 95
Influent flow (l/d)	150	36	18
Filtered Effluent COD (mgCOD/l)	29.0 ± 11.4	36.3 ± 11.3	44.8 ± 11.8
COD removal (%)	96	94	96
Influent TKN (mgN/L)	49.5 ± 9.2	48.0 ± 7.6	60.0 ± 6.3
Influent FSA (mgN/L)	36.1 ± 7.8	34.5 ± 6.5	34.7 ± 4.9
Filtered effluent TKN (mgN/L)	5.8 ± 1.1	4.9 ± 0.8	5.4 ± 0.5
Effluent FSA (mgFSA-N/L)	<1	<1	<1
Effluent Nitrate (mgNO$_3$-N/L)	5.8 ± 2.2	10.1 ± 7.4	19.0 ± 10.2
TKN removal (%)	88	90	90
Influent TP (mgTP-P/L)	57.4 ± 4.7	16.0 ± 1.4	21.9 ± 2.8
Influent OP (mgOP-P/L)	44.3 ± 7.1	13.5 ± 1.4	14.9 ± 1.4
Filtered effluent TP (mgTP-P/L)	21.1 ± 3.2	10.4 ± 1.1	10.5 ± 1.6
P Removal (mgTP-P/L)	36.1	5.6	11.4
Unbio. soluble COD fraction ($f_{SU,CODInf}$)	0.047	0.058	0.043
Aerobic reactor VSS (mgVSS/L)	6814 ± 358	2095 ± 118	2243 ± 162
Aerobic reactor TSS (mgTSS/L)	9392 ± 517	2533 ± 106	2714 ± 178
Aerobic reactor ISS (mgISS/L)	2578 ± 225	438 ± 34	471 + 72
Oxygen utilization rate [mgO/(l.h)]	55.5±4.7	47.0±3.4	30.6±2.5
Nitrate nitrified in aerobic (mgN/L influent)[a]	22.1	34.2	21.5
Nitrate denitrified in anoxic (mgN/L influent)[a]	16.1	15.2	11.2

[a] From nitrate flux balances over the system reactors.

(36.3 mgP/l) indicated that there was substantial growth of PAO biomass and PP synthesis, as expected from the influent readily biodegradable soluble organics (RBCOD) and added 200 mgCOD/l acetate.

With the constant influent COD flux and sludge age, i.e. steady state conditions, the total settleable solids (TSS) and volatile settleable solids (VSS) concentrations in the system reactors did not vary much. The inorganic settleable solids (ISS) concentrations in the aerobic reactors of the MLE systems remained low (438 ± 34 mgISS/l for MLE1 and 471 ± 72 mgISS/l for MLE 2) while that in the UCT system was about five times higher (2578 ± 225 mgISS/l) (Table 5). This difference is in part due to the higher TSS concentration in the UCT system but also due to the high PP content of the PAOs mediating the EBPR. From Ekama and Wentzel (2004), the MLE system reactor ISS concentration is a combination of influent (fixed) ISS and a small ISS contribution from the OHOs (0.15 mgISS/mgOHOVSS) so the VSS/TSS ratios are high. With EBPR, the reactor ISS concentration increases significantly due to the ISS content of PP in PAOs, i.e. 3.826 mgISS/mgPP-P. Therefore, if the PAOs have their maximum PP content ($f_{xBGPP} = 0.35$ mgP/mgPAOVSS, Wentzel et al., 1989), their ISS contribution is $0.15 + 0.35 \times 3.286 = 1.3$ mgISS/mgPAOVSS. This makes the VSS/TSS ratio with EBPR significantly lower (0.727) than in the two MLE systems (~0.826).

3.6. *Determining the WAS unbiodegradable fraction (UPO) with AS models*

The Ekama and Wentzel (1999) method for determining the influent unbiodegradable soluble (USO, $f_{SU,CODInf}$) and particulate (UPO, $f_{xU,CODInf}$) COD fractions simultaneously fractionates the activated sludge VSS into its different components. These VSS components are then separated into biodegradable and unbiodegradable parts from which the unbiodegradable fraction of the WAS is found. For N removal systems there are three VSS components, i.e. (i) OHO biomass (X_{OHO}), (ii) OHO endogenous residue ($X_{E,OHO}$) and (iii) unbiodegradable particulate organics (UPO, $X_{U,Inf}$). For N and P removal systems there are five VSS components, i.e. same three for the N removal systems plus (iv) PAO biomass (X_{PAO}) and (v) PAO endogenous residue ($X_{E,PAO}$). The influent USO fraction ($f_{SU,CODInf}$) is given by the filtered effluent COD ($S_{U,Inf}$)/Total influent COD ($COD_{T,Inf}$) concentrations (Table 5). For the MLE N removal systems, the influent UPO fraction ($f_{xU,CODInf}$) is given by the value which makes the calculated mass of VSS in the reactors equal to the measured VSS mass, where the calculated VSS mass is found from the steady state ND AS model equation (WRC, 1984; Henze et al., 2008) which links the mass of VSS in the system to sludge age and organic load. With the influent USO ($f_{SU,CODInf}$) and UPO ($f_{xU,CODInf}$) fractions known, the concentrations in VSS units of OHO biomass ($X_{OHO,VSS}$), endogenous residue ($X_{U,E,OHO,VSS}$) and UPO ($X_{U,Reac,VSS}$) that make up the VSS in the reactor are also known. This procedure essentially "calibrates" the AS model to the influent wastewater's USO ($f_{SU,CODInf}$) and UPO ($f_{xU,CODInf}$) fractions. Assuming the COD/VSS ratio (f_{COD_VSS}) of the different VSS components to be the same, the biodegradable COD of the MLE systems' WAS is the biodegradable part of the OHO biomass [$f_{COD\_VSS}(1 - f_{E\_OHO})X_{OHO,\ VSS}$] and the unbiodegradable COD is the unbiodegradable part of the OHO biomass ($f_{COD\_VSS} f_{E\_OHO} X_{OHO,VSS}$) and all of the OHO endogenous residue ($f_{COD\_VSS} X_{U,E,OHO,VSS}$) and UPO ($f_{COD\_VSS} X_{U,Inf,VSS}$).

Table 6 – Summary of results for anaerobic digestion systems operated during experimental investigation.

SRT (d)	Primary sludge (AD2)										WAS from MLE 1 system (AD3)										Primary sludge- MLE 1 WAS blend (AD4)									
	10		18		25		40		60		10		18		25		40		60		10		18		25		40		60	
Flow (l/d)	1.20		0.67		0.50		0.30		0.09		1.20		0.67		0.48		0.30		0.08		1.20		0.67		0.50		0.30		0.09	
Sample	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff
COD – UF	5.68	3.91	8.05	4.60	8.91	4.26	18.71	6.68	28.43	10.29	2.67	2.29	3.65	2.51	5.15	3.01	8.05	4.45	11.71	6.22	8.44	5.97	11.65	6.91	13.77	6.87	26.70	12.42	41.46	16.94
COD – F	0.46	0.12	0.82	0.18	1.24	0.25	1.67	0.37	2.63	0.33	0.19	0.07	0.09	0.07	0.06	0.09	0.09	0.03	0.06	0.03	0.46	0.18	0.82	0.20	1.24	0.21	1.67	0.15	2.63	0.20
VFA	0.16	0.00	0.19	0.00	0.20	0.00	0.31	0.03	0.44	0.04	0.16	0.03	0.06	0.01	0.00	0.04	0.06	0.01	0.02	0.03	0.15	0.00	0.17	0.03	0.20	0.00	0.31	0.03	0.44	0.07
TSS	4.94	3.48	5.56	4.20	6.95	3.95	14.75	6.71	19.73	8.93	2.15	1.92	3.05	1.98	4.22	2.43	6.58	4.02	9.49	5.39	7.05	5.72	9.70	7.82	9.70	7.73	19.24	10.78	28.58	14.86
VSS	3.84	2.40	4.49	2.70	5.49	2.62	11.78	4.48	16.34	5.85	1.78	1.54	2.52	1.49	3.48	1.84	5.40	2.82	7.91	3.95	5.60	4.03	7.82	6.11	7.82	5.70	15.45	7.39	23.69	10.60
ISS	1.10	1.08	1.06	1.45	1.46	1.33	2.97	2.23	3.39	3.07	0.37	0.38	0.53	0.49	0.74	0.59	1.18	1.21	1.59	1.44	1.45	1.69	1.88	1.71	1.88	2.03	3.79	3.38	4.90	4.26

SRT (d)	WAS from MLE 2 (AD5)										WAS from UCT NDBEPR system (AD1)													
	10		18		25		40		60		10		12		18		20		25		40		60	
Flow (l/d)	1.50		0.83		0.60		0.30		0.09		1.60		1.33		0.89		0.80		0.64		0.40		0.083	
COD – UF	3.03	2.59	6.72	5.20	8.21	5.91	17.69	12.05	24.75	16.43	9.36	7.52	9.36	7.42	10.06	7.23	9.36	7.13	9.59	6.95	10.13	6.38	10.42	6.08
COD – F	0.04	0.04	0.04	0.04	0.06	0.06	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.04	0.04	0.04	0.04	0.01	0.01	0.03	0.03
VFA	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.01	0.00	0.02	0.00	0.02	0.00	0.03	0.00	0.01	0.00	0.02	0.00	0.00
TSS	2.59	2.24	5.52	4.24	6.74	4.96	14.11	9.76	20.26	13.07	8.60	7.21	8.60	7.30	9.18	7.40	8.60	7.25	9.88	7.20	9.49	6.73	9.87	6.57
VSS	2.07	1.70	4.55	3.37	5.54	3.88	12.07	7.85	16.74	10.09	6.48	5.04	6.48	4.97	6.92	4.93	6.48	4.89	6.58	4.76	6.99	4.32	7.17	4.18
ISS	0.52	0.54	0.98	0.87	1.20	1.08	2.03	1.91	3.52	2.98	2.11	2.17	2.11	2.33	2.25	2.46	2.11	2.36	3.30	2.44	2.50	2.41	2.70	2.27

For the UCT (N and P removal) system, the influent UPO fraction ($f_{xU,CODInf}$) is found by the same iterative procedure except the calculated VSS is based on the NDEBPR AS model of Wentzel et al. (1990) or Henze et al. (2008). This AS model includes PAOs and so also requires the measured influent BSO (RBCOD) concentration (S_{bsi}) to correctly divide the influent biodegradable COD between the OHOs and PAOs via the fermentation kinetics. Once the correct influent UPO fraction ($f_{xU,CODInf}$) is found which matches the calculated VSS mass in the system to that measured, then, with the same P/VSS ratio for all five of the VSS components ($f_{P\_VSS} = 0.025$ mgP/mgVSS), the polyphosphate (PP) content of the PAOs is determined by matching the calculated P removal with that observed. Again assuming the COD/VSS ratio (f_{COD_VSS}) of the different VSS components to be the same, the biodegradable COD of the UCT system WAS is the biodegradable part of the OHO and PAO biomass [$f_{COD\_VSS}(1 - f_{E\_OHO}) X_{OHO,VSS} + f_{COD\_VSS}(1 - f_{E\_PAO})X_{PAO,VSS}$] and the unbiodegradable COD is the unbiodegradable part of the OHO and PAO biomass [$f_{COD\_VSS}(f_{E\_OHO})X_{OHO,VSS} + f_{COD\_VSS}(f_{E\_PAO})X_{PAO,VSS}$] and all of the OHO and PAO endogenous residue ($f_{COD\_VSS}X_{U,E,OHO,VSS} + f_{COD\_VSS}X_{U,E,PAO,VSS}$) and UPO ($f_{COD\_VSS}X_{U,Reac,VSS}$). With f_{E_OHO} and $f_{E\_PAO} = 0.08$ (discussed below), Table 7 lists the unbiodegradable COD fractions of the raw and settled wastewaters and WAS from the three AS systems determined in this way. The UPO COD fraction ($f_{xU,CODInf}$) of the PS was calculated by mass balance difference between the raw and settled wastewater COD concentrations determined for the MLE systems.

3.7. *Determining the PS and WAS unbiodegradable fraction with AD model*

The unbiodegradable COD fractions of the PS and three WAS fed to the ADs were determined from the AD results in two ways: (i) the effluent COD as a fraction of the influent COD for the 60 d AD, which assumes all the biodegradable organics are utilized at 60 d sludge age, and (ii) by applying the Sötemann et al. (2005) steady state AD model to the measured influent and effluent COD concentrations from the 10 to 60d ADs. Briefly this procedure is: (i) The assumption that the effluent unbiodegradable soluble COD (USO, $S_{U,Eff}$) and VFA (S_{VFA}) concentrations are negligible (<0.1%) is checked, (ii) the influent unbiodegradable particulate (UPO) COD concentration ($X_{U,Inf}$) is set to $f_{xU,CODInf} \times COD_{T,Inf}$, where $f_{xU,CODInf}$ is the unbiodegradable COD fraction of the influent sludge. This $X_{U,Inf}$ passes directly though the AD so that $X_{U,Eff} = X_{U,Inf}$, where $X_{U,Eff}$ is the effluent UPO COD concentration. The total effluent COD ($COD_{T,Eff}$) therefore is the sum of the non-utilized biodegradable COD ($X_{B,Eff}$), the UPO ($X_{U,Eff}$) and the proportion (E) of the biodegraded COD transformed to AD sludge mass, i.e. $COD_{T,Eff} = X_{B,Eff} + f_{xU,CODInf}COD_{T,Inf} + E [COD_{T,Inf} (1 - f_{xU,CODInf}) - X_{B,Eff}]$. In this equation, E is known from the AD sludge age (SRT) and AD biomass constants (Y, b, f_E) and $COD_{T,Inf}$ and $COD_{T,Eff}$ are the measured influent and effluent particulate COD concentrations – unfiltered (UF) minus filtered (F). Therefore, with an estimate of $f_{xU,CODInf}$, S_{bpe} can be calculated for each sludge age (E) value. With $X_{B,Eff}$ known, the acidogen (acid forming) biomass concentration (X_{AFO}, gCOD/l) and volumetric hydrolysis rate [r_{hyd}, gCOD/

Table 7 – Influent unbiodegradable particulate ($f_{xU,CODInf}$) and soluble ($f_{SU,CODInf}$) COD fractions for the primary sludge and the MLE2, MLE1 and UCT NDEBPR systems calculated with the ND and NDEBPR models.

Test period	PS	MLE 2 fed Raw WW			MLE 1 fed Settled WW			UCT system fed Settled WW			
		WW	WW	WAS	WW	WW	WAS	WW	WW	WW	WAS
	$f_{xU,CODInf}$ [a]	$f_{xU,CODInf}$ [a]	$f_{SU,CODInf}$	$f_{xU,CODInf}$ [c]	$f_{xU,CODInf}$ [a]	$f_{SU,CODInf}$	$f_{xU,CODInf}$ [c]	$f_{xU,CODInf}$ [b]	$f_{SU,CODInf}$ [b]	S_{bsi}/S_{ti} [b]	$f_{xU,CODInf}$ [c]
1	0.28	0.15	0.04	0.61	0.04	0.05	0.46	0.18	0.04	0.37	0.52
2	0.28	0.16	0.04	0.63	0.06	0.05	0.05	0.19	0.04	0.33	0.55
3	0.34	0.15	0.04	0.62	0.02	0.04	0.42	0.16	0.02	0.3	0.53
4	0.33	0.17	0.06	0.64	0.07	0.09	0.51	0.19	0.05	0.38	0.53
5	0.25	0.13	0.04	0.6	0.05	0.05	0.47	0.17	0.05	0.32	0.53
Ave	0.3	0.15	0.04	0.62	0.05	0.06	0.47	0.18	0.04	0.34	0.53

[a] Based on ND steady state model WRC (1984) or Henze et al. (2008).

[b] S_{ti} includes 200 mgCOD/l acetate dosed to settled WW: [2]Based on NDEBPR steady state model of Wentzel et al. (1990) or Henze et al. (2008).

[c] Unbiodegradable COD fraction of WAS = $(f_{E\_OHO}X_{OHO} + f_{E\_PAO}X_{PAO} + X_{U,E,OHO} + X_{U,E,PAO} + X_{U,Inf}/(X_{VSS}))$ where $f_{E\_OHO} = f_{E\_PAO} = 0.08$.

(l.d)] can be calculated from steady state AD model. With $X_{B,Eff}$, X_{AFO} and r_{hyd} known, the constants in any of four hydrolysis rate equations, i.e. (i) first order [$r_{hyd} = k_h X_{B,Eff}$], (ii) specific first order [$r_{hyd} = k_H X_{B,Eff} X_{AFO}$], (iii) Monod [$r_{hyd} = k_m X_{B,Eff}/(K_s + X_{B,Eff})X_{AFO}$], and (iv) saturation [$r_{hyd} = k_M(X_{B,Eff}/X_{AFO})/\{K_S+(X_{B,Eff}/X_{AFO})\}X_{AFO}$] can be calculated as shown by Sötemann et al. (2005) and Ikumi et al. (2011). For the first order and specific first order rates, one expects the k_h and k_H to be constant with sludge age (SRT), but they are not (in fact they tend to increase linearly with (SRT). So an average (k_{ave}), standard deviation (k_{stdev}) and coefficient of variation ($C_{var} = k_{stdev}/k_{ave}$) are calculated for the range of sludge ages tested. The $f_{xU,CODInf}$ that gives the lowest C_{var} is deemed the best estimate of the $f_{xU,CODInf}$ value of the sludge for these two hydrolysis kinetic equations.

For the Monod and saturation rate equations, the $X_{B,Eff}$, X_{AFO} and r_{HYD} are calculated in the same way for each sludge age. Then the constants (k_m, K_s, k_M and K_S) in the rate equations are obtained with (i) a curve-fitting programme like R or Curve Expert, or (ii) with different linearization methods (Sötemann et al., 2005), which also give the correlation coefficient (R^2). The procedure is repeated for different selected influent COD unbiodegradable fractions ($f_{xU,CODInf}$). The $f_{xU,CODInf}$ that yields the highest R^2 is accepted to be the best estimate of the $f_{xU,CODInf}$ value for the influent organics in terms of the Monod and saturation hydrolysis kinetics. The $f_{xU,CODInf}$ values so obtained for the different hydrolysis kinetic rates are not the same but are close to one another (<5% variation).

For a particular sludge, each of the different hydrolysis rate equations yields a slightly different UPO ($f_{xU,CODInf}$) fraction within a narrow range. So an average fraction is selected to apply for all four hydrolysis rate equations. The average UPO ($f_{xU,CODInf}$) of the PS and three AS systems' WAS so determined are listed in Table 8 together with the AS model calculated values. Also the hydrolysis rate constants obtained in the four rate equations for the different sludges are listed in Tables 9 and 10, together with the rates for PS determined in previous investigations. The percentage biodegradable COD removal versus AD sludge age (SRT) obtained from these rate equations and experimentally measured for the different sludges are compared in Figs. 3 and 4.

4. Results and discussion

4.1. *Comparing the WAS UPO fractions obtained from AS and AD models*

From Table 8, it can be seen that the average UPO fraction of WAS from MLE1, MLE2 and UCT systems calculated with the AS models using the death regeneration values of OHO and PAO endogenous residue, i.e. row AS[4] in Table 8, are 0.47, 0.62 and 0.53 respectively. These fractions are nearly the same as the UPO fractions determined with AD model for Monod and saturation hydrolysis kinetics, i.e. 0.47, 0.62 and 0.54 respectively (row AD). Also, the average UPO fraction of WAS from the MLE1, MLE2 and UCT systems calculated with the AS

Table 8 – Unbiodegradable particulate organic (UPO) fractions of primary sludge (PS) and WAS from MLE2 (fed raw WW), MLE1 (fed settled WW) and UCT (fed settled WW) determined from the steady state AS (WRC, 1984; Henze et al., 2008) and AD (Sötemann et al., 2005) models and the 60d AD results.

	PS	Waste activated sludge			Mixture	PS^1	PS^2	PS^3
		MLE1	MLE2	UCT	PS+MLE1	Izzett	O'Rourke	Ristow
AS^4	0.30	0.47	0.62	0.53	0.36			
AS^5	0.30	0.57	0.67	0.61	0.41			
AD	0.31	0.47	0.62	0.54	0.37	0.36	0.33	0.34
60d AD	0.31	0.53	0.66	0.58	0.40			

PS^1 from Sötemann et al. (2005), determined from Izzett et al. (1992) data.
PS^2 from Sötemann et al. (2005), determined from O'Rourke (1967) data.
PS^3 from Ristow et al. (2004).
AS^4 – WAS f'_{Sup} from biomass UPO fraction for AS death regeneration (i.e. $f'_{E\_OHO} = 0.08$; $f'_{E\_PAO} = 0.08$).
AS^5 – WAS f'_{Sup} from biomass UPO fractions for AS endogenous respiration (i.e. $f_{E\_OHO} = 0.20$; $f_{E\_PAO} = 0.25$).

Table 9 – First order (k_h) and specific first order (k_H) hydrolysis rates observed in this investigation for ND (MLE1 and MLE2) and NDEBPR (UCT) WAS and primary sludge (PS) in this and other investigations.

Sludge	UPO	Rate	Mean	Std Dev	C_{var}	k vs SRT equation	CC[d]
MLE1	0.47	^1k_h	0.174	0.088	0.567	$= 0.0033 + 0.0413 \times SRT$	0.8415
WAS		^2k_H	4.376	1.945	0.445	$= 0.0963 + 0.970 \times SRT$	0.974
MLE2	0.62	^1k_h	0.115	0.059	0.384	$= 0.070 + 0.0028 \times SRT$	0.82
WAS		^2k_H	3.966	1.819	0.206	$= 1.147 + 0.092 \times SRT$	0.98
UCT	0.54	^1k_h	0.127	0.084	0.661	$= 0.070 + 0.0028 \times SRT$	0.895
WAS		^2k_H	3.421	2.633	0.770	$= 0.0332 + 0.0041 \times SRT$	0.875
PS	0.31	^1k_h	0.860	1.34	1.56	$= -0.077 + 0.0132 \times SRT$	0.924
This		^2k_H	18.05	27.04	1.50	$= -0.303 + 0.372 \times SRT$	0.85
PS	0.36	^1k_h	0.515	0.032	0.062	$= 0.432 + 0.0065 \times SRT$	0.78
Izzett[a]		^2k_H	0.322	0.047	0.146	$= 0.228 + 0.00737 \times SRT$	0.78
PS	0.34	^1k_h	2.081	0.881	0.423	$= 1.03 + 0.398 \times SRT$	0.762
O'Rourke[b]		^2k_H	1.493	0.565	0.378	$= -1.50 + 0.2042 \times SRT$	0.874
PS	0.33	^1k_h	0.992	0.492	0.496	No correlation	–
Ristow[c]		^2k_H	0.014	0.001	0.095	No correlation	–

[a] Izzett et al. (1992) data – see Sötemann et al. (2005).
[b] O'Rourke (1967) data – see Sötemann et al. (2005).
[c] Ristow et al. (2004).
[d] CC = Correlation Coefficient for the linear k vs SRT equation.

Table 10 – Monod and saturation hydrolysis rates observed in this investigation for ND (MLE1 and MLE2) and NDEBPR (UCT) WAS and primary sludge (PS) in this and other investigations.

AD feed source	Unbio-degradable fraction	Monod kinetics			Saturation kinetics		
		k_m	K_s	R^2	k_M	K_S	R^2
MLE1	0.47	2.094	0.408	0.963	1.603	5.387	0.951
MLE2	0.62	2.482	0.626	0.948	1.524	4.838	0.951
UCT	0.54	2.465	0.607	0.826	1.951	9.109	0.919
PS[a]	0.31	4.300	1.523	0.932	1.796	7.962	0.942
PS[b]	0.36	3.34	6.76	>0.90	5.27	7.98	>0.90
PS[c]	0.34	2.004	0.355	>0.90	2.047	0.263	>0.90
PS[d]	0.33	0.243	640	ND	11.2	13	ND

[a] This investigation.
[b] Sötemann et al. (2005), determined using data from Izzett et al. (1992).
[c] Sötemann et al. (2005), determined using data from O'Rourke (1967).
[d] Ristow et al. (2004 data); ND = Not determined.

models using the endogenous respiration values of OHO and PAO endogenous residue ($f_{E\_OHO} = 0.20$; $f_{E\_PAO} = 0.25$) are 0.57, 0.67 and 0.61 respectively, i.e. row AS^5 in Table 8. These are reasonably close to the UPO fractions measured on 60d sludge ADs, i.e. 0.53, 0.66 and 0.58 respectively. It would appear that the UPO fraction calculated from the AD model is consistently underestimated compared with that measured on the 60 d ADs. If it is accepted that the best estimate of the sludge UPO fraction is calculated from the AD results over the full sludge age range, then the best AS model estimate for the sludge UPO in AD is based on the death-regeneration model values of OHO and PAO endogenous residue (i.e. $f_{E\_OHO} = 0.08$; $f_{E\_PAO} = 0.08$).

Being a wastewater characteristic, one expects the influent UPO ($f_{xU,CODInf}$) fraction for same WW fed to different systems to be the same. However, this is not the case – the influent UPO ($f_{xU,CODInf}$) fraction of the settled wastewater determined for the UCT system is significantly higher (0.18) than that determined for the MLE1 system (0.05). Although the higher influent UPO ($f_{xU,CODInf}$) fraction in the UCT system is in part the result of the membranes (Du Toit et al., 2007 reported a higher $f_{xU,CODInf}$ for a membrane UCT system than a parallel settling tank UCT system fed the same wastewater), a considerably higher influent UPO ($f_{xU,CODInf}$) for NDEBPR systems than in ND systems has been consistently observed in the past in the UCT laboratory (Ekama and Wentzel, 1999). So this result in this investigation is not unusual. The consequence of this considerably higher influent UPO ($f_{xU,CODInf}$) fraction for NDBEPR systems is that the UPO component ($X_{U,Inf}$) of the VSS in these systems is significantly higher than in ND systems. The similar UPO fraction of the UCT system WAS obtained from the AS and AD models shows this difference is carries through to the UPO measured on the AD. This indicates that the difference in influent UPO fractions found in ND and NDEBPR systems fed the same wastewater appears to be real and not an artifice of the AS models. No reason for this can be advanced at this time.

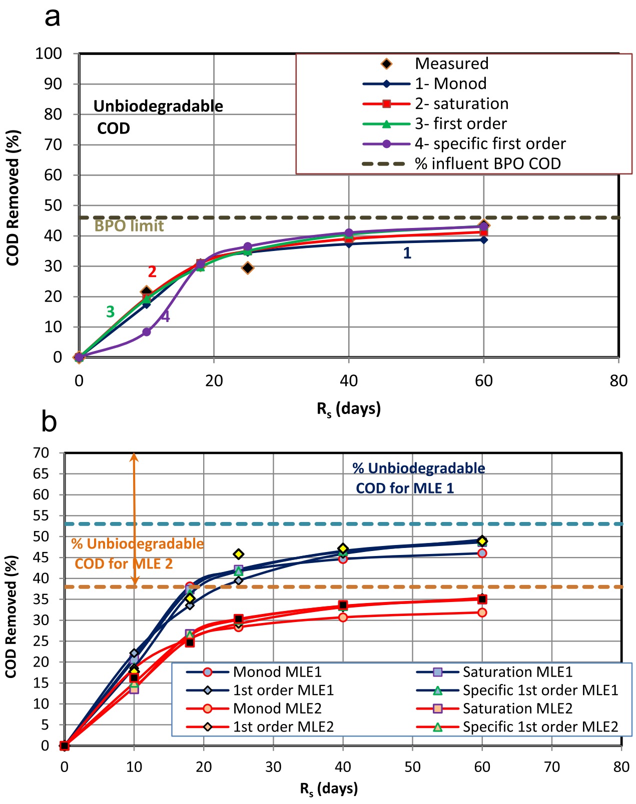

Fig. 3 – a and b: *Comparison of* percentage biodegradable COD removal versus AD sludge age obtained for the waste activated sludge from (a, top) the UCT system *($f_{xU,CODInf} = 0.54$) and (b, bottom) the MLE2 system fed raw wastewater ($f_{xU,CODInf} = 0.62$) and MLE1 system fed settled wastewater ($f_{xU,CODInf} = 0.47$).*

Once calibrated to a particular AD experimental data set, the different hydrolysis rate equations predict the percentage COD removal for that data set similarly well (Figs. 3 and 4). This means it is not possible to determine experimentally which hydrolysis rate equation is best for modelling AD so the best equation from a mathematical modelling perspective is selected – usually saturation due to it's independence of influent COD and bulk liquid biomass concentrations. The three types of WAS hydrolyse similarly slowly (Fig. 3), so digesting WAS from ND or NDEBPR activated sludge systems treating raw or settled WW require similar long sludge ages. The PS from this investigation (Fig. 4a) hydrolysed similarly slowly as the WAS which is significantly more slowly than the PS from previous investigations (Fig. 4b–d). The reason is not clear because the sludge source was the same as Ristow et al. (2004).

5. Conclusions

This research paper investigates the fate of influent unbiodegradable particulate organics (UPO) and activated sludge generated (endogenous residue) UPO in a plant wide set-up. The results provide experimental evidence that the unbiodegradability of the influent wastewater organics as determined by AS and AD models remains approximately consistent throughout the WWTP and hence can be modelled to be conserved in this way when linking the fully aerobic, ND or NDEBPR AS systems to AD systems in plant-wide WWTP models. The remaining influent biodegradable organics get transformed to active organisms (OHO and PAO) in the fully aerobic, ND and NDEBPR AS systems, part of which undergo endogenous respiration to form endogenous residue (which becomes part of the UPO in WAS). In AD, the concentration of BPO not hydrolysed depends on the kinetic rate of sludge hydrolysis. The hydrolysis kinetic rate and unbiodegradable particulate fraction of the different sludges were determined from the measured AD influent and effluent COD concentrations over the sludge age range of 10–60 days. The WAS UPO (assuming 8% of OHO and PAO biomass was unbiodegradable; i.e. $f'_{E\_OHO} = f'_{E\_PAO} = 0.08$) measured on the 60 d AD and determined from the hydrolysis kinetics calibration matched reasonably closely (within experimental system operation error) to the UPO determined for the WAS from measured AS system performance. This shows that the material that is unbiodegradable in AS systems (i.e. endogenous residue and influent UPO) is not significantly further degraded in the AD system, even at very long sludge ages (60 d) and so in the absence of sludge conditioning systems,

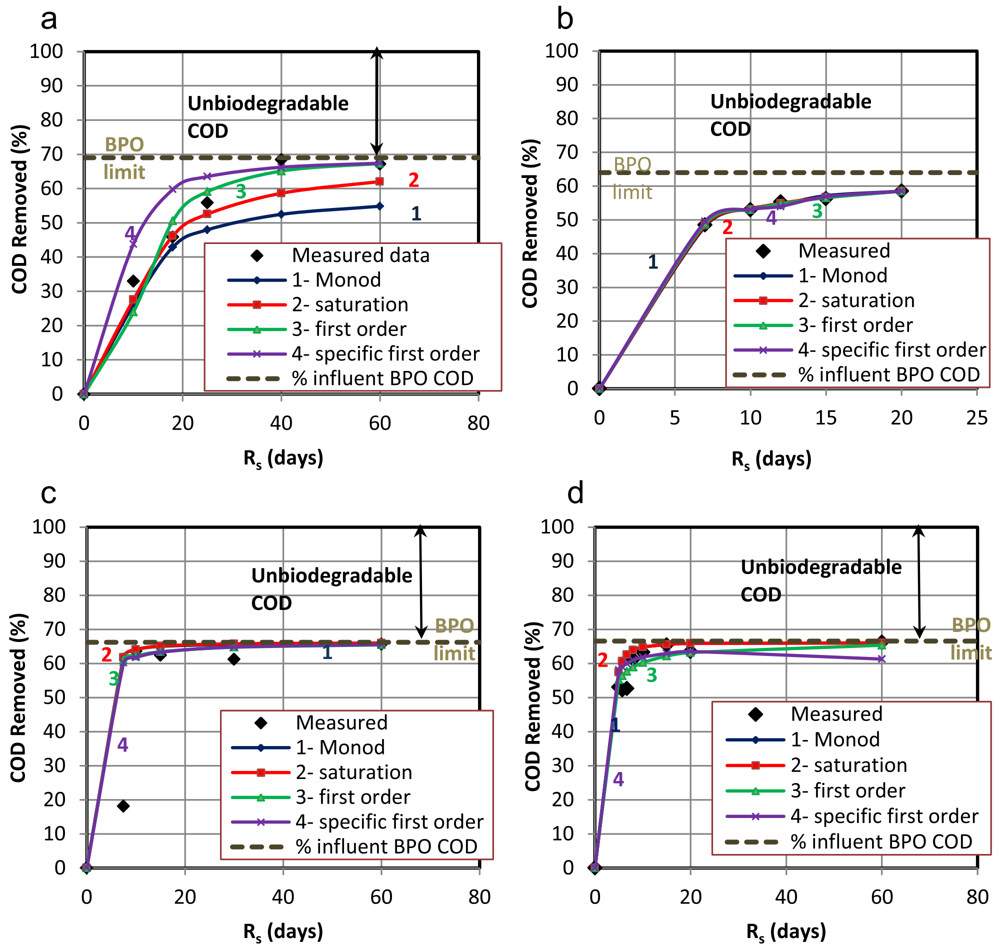

Fig. 4 – a–d: Comparison of percentage biodegradable COD removal versus AD sludge age for primary sludge obtained from the data of (a, top left) this investigation ($f_{xU,CODInf} = 0.31$), (b, top right) Izzett et al. (1992) in Sötemann et al. (2005) ($f_{xU,CODInf} = 0.36$), (c, bottom left) O'Rourke (1967) data in Sötemann et al. (2005) ($f_{xU,CODInf} = 0.34$), and (d, bottom right) Ristow et al. (2004) ($f_{xU,CODInf} = 0.33$).

can be assumed to remain unbiodegradable throughout the WWTP.

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