

Contribution of P-bacteria in biological nutrient removal processes to overall effects on the environment

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Abstract P-bacteria can combine denitrification and P-uptake. This category of P-bacteria is abbreviated DPB. Use of DPB in BNR processes, instead of obligate aerobic PAOs, reduces oxygen consumption. Moreover, less COD is needed for the nitrogen removal. Non-required COD can be removed by presettling and used for methanation. This leads to a lower sludge production. As a result, CO₂ emissions are reduced owing to less net energy consumption. Simulation for a planned WWTP with the BCFS[®] process indicates that DPB can save 53–59% of required COD. The optimal ratios of COD/N and COD/P for simultaneous N and P removal are determined to be 3.9–4.5 and 32.2–35.2 at 12–20°C. 80–95% of particulate COD can be removed from the influent, thereby CH₄ production is increased by 154–271%, and the total volume of reactors can be reduced by about 50% compared to a minimised process design. Less net energy consumption over the whole WWTP contributes to a net reduction of the total CO₂ emissions up to 16–21%. The energy production from CH₄ is excessive enough to balance the energy consumption from aeration, dewatering and incineration. It is concluded that contribution of P-bacteria to saving COD has overall positive effects on the environment.

Keywords P-bacteria; BNR; DPB; denitrifying phosphate removal; CO₂ emission; simulation

Nomenclature

ASM = activated sludge model

BCFS[®] = modified UCT process

BNR = biological nutrient removal

COD_{bio} = biodegradable COD (g COD/m³)

COD_{par} = particulate COD (g COD/m³)

COD_{tot} = total COD (g COD/m³)

DPB = denitrifying phosphorus removing bacteria

η_{PNO₃} = reduction factor under anoxic conditions

PAOs = phosphate accumulating organisms

S_A = fermentation products, considered to be acetate (HAc) (g COD/m³)

S_F = fermentable, readily biodegradable organic substrates (g COD/m³)

S_I = inert soluble organic substance (g COD/m³)

SRT = solids retention time (days)

T = temperature (°C)

X_I = inert particulate organic substance (g COD/m³)

X_S = slowly biodegradable substrates (g COD/m³)

X_{TSS} = total suspended solids (g SS/m³)

Introduction

Increasingly stricter effluent standards to control eutrophication not only urge upgrading of existing wastewater treatment plants (WWTPs), but also compel newly planned WWTPs to include nutrient removal. Biological nutrient removal (BNR) has been becoming a major measure in eutrophication control. Based on nitrification and denitrification coupled with enhanced biological phosphorus removal (EBPR), such BNR processes as UCT have been successfully applied in practice (Ekama and Wentzel, 1999).

Complying with stricter effluent standards may result in much more energy consumption and CO₂ emissions. From the point of a more integrated view on environmental aspects, polished effluent quality can easily lead to overall adverse effects on the environment (van Loosdrecht *et al.*, 1997). For this reason, an overall environmental impact analysis should be performed in evaluating BNR processes. If COD need for BNR processes may be minimised, excess COD can be used for methanation, which helps make the processes more sustainable. As a result, the energy consumption is expected to be reduced and thereby CO₂ emissions to be also lowered, which has an overall positive effect on the environment.

Among phosphate accumulating organisms (PAOs) in BNR processes, denitrifying phosphorus removal bacteria (DPB) can contribute to a significant reduction in COD need for the N removal (Kuba *et al.*, 1996a). In reality, this contribution of DPB is quite difficult to be quantitatively determined by experiments. Moreover, the optimal ratios for COD/N and COD/P for integrated N and P removal usually need to be determined by experiments. This often leads to lack of enough information in process design. In other words, presettling for particulate COD is also not easy to be determined without knowing these optimal ratios. If the optimal ratios are ascertained, particulate COD (not required) can be trapped by presettling for methanation. Presettling of particulate COD is also helpful for a volume reduction of reactors.

Compared to experiments, modelling is a good and fast approach to addressing the above questions. Simulation not only easily determines the optimal ratios of COD/N and COD/P, but also clearly indicates the potential of PAOs/DPB in saving COD for the N removal. Moreover, O₂ consumption, excess sludge, N₂ production and so on can be obtained at the same time. This will lead to an easy evaluation of general environmental impacts of WWTPs.

A newly planned WWTP with a modified UCT-type process (BCFS[®]) will be constructed in a town in the Netherlands. With the initial process design (without presettling) of this plant, simulation was initiated to make an approach to answering the concerned questions. Simulation was firstly intended to meet the needs of the nutrient effluent standards (total N ≤ 10 g N/m³, NH₄⁺ - N ≤ 1 g N/m³ and total P ≤ 1 g P/m³). Based on the simulation, particulate COD reduction was tried by new simulation, until finding the optimal ratios of COD/N and COD/P. With the optimal ratios, energy consumption and CO₂ emissions were evaluated.

In this case study, a metabolically structured model for bio-P removal (Smolders *et al.*, 1994; Kuba *et al.*, 1996a; Murnleitner *et al.*, 1997) and the parts of ASM2/2d for COD and N removal (Gujer *et al.*, 1995 and Henze *et al.*, 1999) were employed to simulate the BCFS[®] process. Three full-scale WWTPs with BNR (a Phostrip[®] and two BCFS[®] processes) have been successfully simulated by this combined model (van Veldhuizen *et al.*, 1999, Brdjanovic *et al.*, 2000, and Meijer *et al.*, 2000); the used parameter set was each time the same.

Based on the combined model and the same parameter set, the newly planned WWTP was simulated with the parameters from the original process design. Simulation was implemented by a computer software package, AQUASIM 2.0 (Reichert, 1994).

Methodology

Process design and influent characteristics

The planned WWTP is a BCFS[®] process without presettling, as shown in Figure 1. This modified UCT process is characterised by three internal recirculations, Q_A , Q_B and Q_C . An external recirculation ratio of about 1.2 is maintained for return sludge. The total design volume of five reactors is 10,000 m³ and the volume of final clarifier is calculated to be 2,800 m³. The plant has an average inflow of 8,500 m³/d. The average influent concentrations are listed in Table 1.

Approach to the questions

According to the STOWA method (1996), the influent COD can be divided into different model components (Table 2) for simulation purpose. With the influent characteristics shown in Table 2, the first simulation is conducted, according to the original process design shown in Figure 1. As a TSS concentration of about 5,000 g/m³ in reactors is prescribed by the process design, SRT is depended on the expected TSS value. The SVI of existing BCFS[®] processes is always below 120 ml/g. So it can be assumed that separation of sludge is always good in the final clarifier.

After SRT is determined by the expected TSS concentration, biodegradable and inert particulate COD components (X_S and X_I) are proportionally reduced (a maximum reduction percentage up to 95%) until the effluent quality just satisfies the effluent standards. When X_S and X_I are reduced, the influent N and P are correspondingly decreased as both X_S and X_I contain N (0.03–0.04 g N/g COD) and P (0.01 g P/g COD) contents. At this state, the so-called optimal ratios of COD/N and COD/P can be obtained.

To evaluate contribution of DPB to saving COD for the nitrogen removal, a reduction factor under anoxic conditions, η_{PNO_3} , is set to 0 from its normal value of 0.8. This action effectively switches off denitrifying phosphate removal in simulation. Further simulations are continued at the optimal ratios. In this case, the effluent N and P were increased over the effluent standards. For this case, the influent particulate COD (X_S and X_I) is proportionally increased, until the effluent N and P are lowered to the effluent standards again. The extra COD need (based on COD/N and COD/P) should be of contribution of DPB to improving P and N removal.

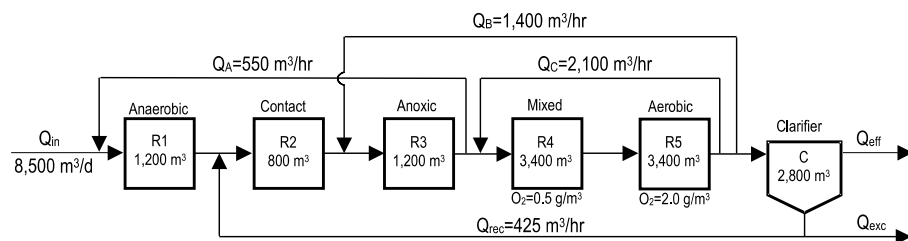


Figure 1 BCFS[®] process design for a planned WWTP in the Netherlands

Table 1 Influent characteristics

COD (g O ₂ /m ³)	BOD ₅ (g O ₂ /m ³)	TKN (g N/m ³)	TP (g P/m ³)
625	250	60	9.5

Table 2 Influent COD components (g/m³)

S_A	S_F	S_I	X_S	X_I	COD _{par} ^{inf}	COD _{bio} ^{inf}	COD _{tot} ^{inf}
75	85	35	275	155	430	435	625

After original process design is minimised for reactor volume with the original influent flow and composition, a model-based evaluation of reduction of reactor volume with pre-settling can be made.

The model and parameters used have been described by van Veldhuizen *et al.* (1999). Small differences from the used model are mentioned in previous papers (Hao *et al.*, 2000a and 2000b).

Evaluation of the simulation model

AQUASIM 2.0 (Reichert, 1994) is used as the simulation software package. Completely mixed reactors are used to simulate the hydraulics of the WWTP. To simulate the plug-flow characteristics for R1, it is divided into three identical compartments.

In practice, there are bacterial activities in the sludge-layer of clarifiers. In the simulation model, the final clarifier is divided into two compartments: a supernatant compartment and a sludge-layer compartment. In the sludge-layer compartment, all the 21 processes concerning hydrolyses, PAOs, heterotrophic and autotrophic organisms are activated. The volume of the sludge-layer compartment is set to 40% of the final clarifier volume.

12°C is the design-based temperature and is therefore applied for simulation. As a comparison, 20°C is also used for simulation. All simulations are calculated over a period of 300 days to attain a complete steady state.

O₂ consumption, N₂ production and excess sludge

In order to obtain O₂ consumption and N₂ production directly from the simulation model, two extra components (a second O₂ not exchanging with the gas phase and N₂) are introduced in the stoichiometric matrix.

Sludge production is calculated from the discharge rate and concentration of excess sludge. For an activated sludge system, Q_{exc} can be calculated by:

$$Q_{exc} = \frac{V \cdot Q_{rec}}{(Q_{in} + Q_{rec}) \times SRT - V} \quad (1)$$

where Q_{exc} = discharge rate of excess sludge (m³/d), V = total volume of reactors (m³), Q_{rec} = return sludge rate (m³/d) and Q_{in} = inflow rate (m³/d).

In the BCFS[®] process shown in Figure 1, return sludge is recirculated into R2 instead of R1. Therefore, R1 has a lower TSS concentration and V is summed as:

$$V = 0.61V_1 + V_2 + V_3 + V_4 + V_5 \quad (2)$$

TSS concentration is calculated from all particulate components by:

$$X_{TSS} = \sum X_i / (1.4 \times 0.72) \quad (3)$$

where X_i = particulate components concentration (g COD or P/m³), 1.4 g COD/g VSS = COD of biomass, and 0.72 = ratio between VSS and TSS (i.e. ash content = 0.28).

Energy and CO₂ balances

As a complete plant, the planned WWTP should also include sludge disposal processes such as digestion, dewatering and incineration. Therefore, energy and CO₂ balances for the plant have to be made as a whole. Four factors are generally taken into account for the energy consumption (E^{cons}): 1) aeration (E_{aer}); 2) sludge dewatering (E_{dew}); 3) sludge incineration (E_{inci}); and 4) the energy (CH₄) production by sludge digestion (E_{CH_4}). The net energy consumption (E^{net}) can be expressed as:

$$E^{\text{net}} = E_{\text{CH}_4} - E^{\text{cons}} = E_{\text{CH}_4} - (E_{\text{aer}} + E_{\text{dew}} + E_{\text{inci}}) \quad (4)$$

In the calculation of CO₂ emissions, two sources must be taken into account: 1) COD oxidation ($\Phi_{\text{CO}_2}^{\text{COD-oxi}}$) and 2) power generation ($\Phi_{\text{CO}_2}^{\text{pow}}$). The former CO₂ emission is due to biological COD oxidation, digestion, and sludge incineration. The CO₂ production from COD is calculated assuming a molar formula of the organic carbon of CH₂O. The net CO₂ emissions (Φ_{CO_2}) is calculated as:

$$\begin{aligned} \Phi_{\text{CO}_2} &= \text{COD}_{\text{CO}_2}^{\text{COD-oxi}} + \Phi_{\text{CO}_2}^{\text{pow}} \\ &= \left[(\Phi_{\text{COD}}^{\text{inf}} - \Phi_{\text{COD}}^{\text{eff}}) / \text{COD}_{\text{CH}_2\text{O}} \right] \times M_{\text{CO}_2} + \left[-E^{\text{net}} / (\Delta H_{\text{CH}_4} \times \eta) \right] \times (M_{\text{CO}_2} / M_{\text{CH}_4}) \end{aligned} \quad (5)$$

where $\Delta H_{\text{CH}_4} = 50$ MJ/kg, heat of CH₄ combustion (Janssen, 1991); $\eta = 0.4$, power generation efficiency by CH₄ production; $M_{\text{CO}_2} = 44$ g CO₂/mol, molecular weight of CO₂; $M_{\text{CH}_4} = 16$ g CH₄/mol, molecular weight of CH₄; and $\text{COD}_{\text{CH}_2\text{O}} = 32$ g COD/mol, COD of CH₂O.

CH₄ production from digestion of primary and secondary sludge can be calculated by a conversion factor, $\text{CH}_4^{\text{CODCH}_2\text{O}} = 0.25$ g CH₄/g COD_{CH₂O}, based on the stoichiometric formula:



It is assumed that biodegradable COD (X_S) from presettling can be completely transformed into CH₄ and that COD of biomass (X_{AUT} , X_{H} , X_{PAO} , X_{PHB} and X_{GLY}) from excess sludge can be partly (90%) transformed into CH₄. The inert COD (X_I) is considered non-biodegradable in methanation. The calculations of E_{aer} , E_{dew} , E_{inc} and E_{CH_4} are based on the methods described by van Loosdrecht *et al.* (1997), assuming that dewatering of digested sludge is done by centrifugation and that temperature in incineration is 250°C.

For a simplification of calculation, the composition of ammonium after dewatering is assumed not to return to the influent. Normally this is included in the influent composition. So this line can be removed from the paper.

Results and discussion

Simulation for the process design

With the process design shown in Figure 1, the first simulation is conducted with the influent characteristics listed in Tables 1 and 2. When the expected TSS concentration of about 5,000 g/m³ in reactors are reached, the corresponding SRTs are 19 and 21.5 days at 12 and 20°C. The major results from simulation are shown in Table 3.

Column 2 in Table 3 shows that the process design can easily satisfy the effluent standards. At the high ratios of COD/N (7.3) and COD/P (45.8), low effluent concentrations of N (<5 g N/m³) and P (<0.5 g P/m³) are realised. Under these conditions, a question is raised. May ratios of COD/N and COD/P be lowered to save COD for methanation? A prerequisite is that the effluent standards have to be obeyed. For this reason, a second simulation is continued.

Optimal ratios of COD/N and COD/P

To testify the possibility for COD reduction, the second simulation is initiated with the same SRTs as obtained in the first simulation. Supposing a presettling unit, particulate COD ($X_S + X_I$) in the influent can be thus reduced. When particulate COD ($X_S + X_I$) is decreased by 80% and 95% at 12 and 20°C respectively, the effluent quality just correctly satisfies the effluent standards. The results are shown in Column 3 of Table 3.

Table 3 Simulation results

Parameters (1)		Standard COD ($\eta_{\text{PNO}_3}=0.8$) (2)		Presetting ($\eta_{\text{PNO}_3}=0.8$) (3)		Presetting ($\eta_{\text{PNO}_3}=0$) (4)		Presetting ($\eta_{\text{PNO}_3}=0$) (5)	
		12°C	20°C	12°C	20°C	12°C	20°C	12°C	20°C
		SRT	days	19	21.5	19	21.5	19	21.5
COD _{tot} ^{inf}	g/m ³	625	625	281	217	281	217	570	476
COD _{bio} ^{inf}	g/m ³	435	435	215	174	215	174	400	340
COD _{par} ^{inf}	g/m ³	430	430	86	22	86	22	375	281
COD _{par} ^{inf} /430	%	100	100	20	5	20	5	87	65
COD _{tot} ^{eff}	g/m ³	43	42	37	36	37	36	41	39
N _{tot} ^{inf}	g N/m ³	60.0	60.0	47.6	45.2	47.6	45.2	58.1	54.6
N _{tot} ^{eff}	g N/m ³	5.5	4.3	10.0	9.9	12.6	14.0	10.0	10.0
NH ₄ ⁺ ^{eff}	g N/m ³	0.5	0.2	0.3	0.2	0.3	0.2	0.4	0.2
NO ₃ ^{-eff}	g N/m ³	4.3	3.5	9.2	9.3	11.9	13.4	9.0	9.4
P _{tot} ^{inf}	g P/m ³	9.5	9.5	6.1	5.4	6.1	5.4	9.0	8.0
P _{tot} ^{eff}	g P/m ³	0.2	0.2	0.2	0.2	0.7	1.4	0.2	0.3
PO ₄ ^{-eff}	g P/m ³	0	0	0	0	0.6	1.2	0	0.1
MLSS	g SS/m ³	5,010	5,010	1,666	952.5	1,773	1,039	4,516	3,545
PAO/VSS	%	26.7	28.5	35.1	55.9	19.2	26.6	20.4	23.9
SS _{tot} ^{inf}	g SS/m ³	426	426	88	22	88	22	372	279
SS _{tot} ^{eff}	g SS/m ³	5.7	5.7	2.0	1.2	2.0	1.2	5.1	4.0
COD _{bio/N} ^{inf}		7.3	7.3	4.5	3.9	4.5	3.9	6.9	6.2
COD _{bio/P} ^{inf}		45.8	45.8	35.2	32.2	35.2	32.2	44.4	42.5
$\Phi_{\text{SS}}^{\text{exc}}$	kg SS/d	2,501	2,222	835.1	408.7	873.7	461.1	2,243	1,563
OC _{net}	kg O ₂ /d	3,246	3,553	2,104	2,005	2,112	2,028	3,156	3,078
$\Phi_{\text{N}_2}^{\text{prod}}$	kg N ₂ /d	178.4	192.3	139.3	142.1	126.6	121.3	155.4	157.6

Due to a reduction of particulate COD in the influent, TSS concentrations in reactors sharply decrease to 1,666 and 953 g/m³ at 12 and 20°C respectively. Although a long SRT can help increase TSS concentration in reactors, it can also lead to limit the capacity for intracellular poly-P accumulation in sludge (van Loosdrecht *et al.*, 1996). For this reason, SRT instead of TSS is kept constant in the second simulation.

This simulation indicates that a presettling unit can be added in the process design to trap a large amount of particulate COD for methanation. After 80% and 95% of particulate COD is reduced, the optimal ratios of COD/N and COD/P are obtained: COD_{bio}^{inf}/N = 4.5 or 3.9 and COD_{bio}^{inf}/P = 35.2 or 32.2 at 12 or 20°C.

Contribution of DPB to reduction of COD in the N removal

At the optimal ratios of COD/N and COD/P, the reduction factor under anoxic conditions, η_{PNO_3} , is set to 0 from the standard value, 0.8, to switch off the activity of denitrifying phosphate removal (only for simulation purpose, not realistic). This action implies that uptake of phosphate is prescribed to aerobic conditions. The simulation results are shown in Column 4 of Table 3.

As expected, the effluent quality exceeds the effluent standards; both effluent nitrate and phosphate are increased. Only heterotrophic bacteria perform ordinary denitrification in this case. Obviously, COD is not enough to accomplish ordinary denitrification and aerobic uptake of phosphate. Thus, COD in the influent has to be increased to satisfy the effluent standards.

When particulate COD in the influent is increased up to 87% and 65% of the standard particulate COD (430 g/m³) at 12 and 20°C, the effluent standards are reached again, as shown in Column 5 of Table 3. At this state, the ratios of COD/N and COD/P are: COD_{bio}^{inf}/N = 6.9 or 6.2 and COD_{bio}^{inf}/P = 44.4 or 42.5 at 12 or 20°C. These ratios are much higher than the optimal ones (Column 4), showing the positive effects of DPB on reduction of COD for the N removal.

Based on the ratios of COD/N and COD/P obtained in the two cases, a contribution of DPB to reduction of COD in the N removal can be calculated. At 12°C, the saved COD per gram nitrogen equals to 2.4 g COD/g N (=6.9–4.5), and the saved COD per gram phosphorus equals to 9.2 g COD/g P (= 44.4–35.2). At 20°C, the saved COD is 2.3 g COD/g N (6.2–3.9) and 10.3 g COD/g P (42.5–32.2) respectively. Reduction of COD is simulated between 53% and 59%, which is close to a calculated value of about 50% (Kuba *et al.* 1996a).

Simulation can also indicate proportion of PAO in biomass. As shown in Table 3, proportion of PAO in biomass is different without and with presettling. Column 2 indicates that proportion of PAO is between 26.7% and 28.5% without presettling, while it is increased to 35.1–55.9% with particulate COD presettling of 80–95%. These data are very close to an experimental observation (van Loosdrecht *et al.*, 1997).

Reduction of reactor volume with presettling

The simulation for the process design (Column 2 in Table 3) indicates that reactor volume is big enough to treat the raw influent to the effluent standards. For the daily average inflow (8,500 m³/d) and the influent quality shown in Tables 1 and 2, reactor volume can be minimised. To make a comparison of volume reduction between no presettling and presettling, a minimised process design is needed. For this reason, further simulation is followed to acquire the information about the minimised reactor volume with the same inflow and the water quality as in the process design (Column 2 in Table 3). The results and reactor volume are shown Table 4.

With presettling, the practical volume of reactors can be reduced until the effluent satisfies the standards. According to the influent with presettling (Column 3 in Table 3), simulations are conducted to obtain the information of the reduced volume of reactors. The simulation results are shown in Table 4.

Table 4 indicates that the total volume of reactors with presettling can be reduced by about 50%, compared to the minimised process design.

Energy consumption and CO₂ emissions

The calculations for energy consumption and CO₂ emissions are based on the two cases shown in Table 3: standard COD without presettling (Column 2) and reduced COD with presettling (Column 3). The results are listed in Table 5.

As shown in Table 5, the CO₂ emission from COD oxidation is basically fixed between 6,800 and 6,900 kg CO₂/d. This amount of CO₂ has actually accounted the total CO₂ emission from the COD removal from the influent, regardless of either biological COD oxidation, or CH₄ combustion after digestion (COD→CH₄→CO₂), or inert COD (X_i) combustion in

Table 4 Minimisation of the process design and reduction of reactor volume with presettling

Parameters (1)		Minimisation (2)		Presettling (3)	
		12°C	20°C	12°C	20°C
MLSS	g SS/m ³	5,040	5,040	4,985	5,006
SRT	days	11	7.5	21	32
COD _{tot} ^{eff}	g SS/m ³	42	42	41	41
N _{tot} ^{eff}	g N/m ³	7.5	7.7	9.9	9.8
NH ₄ ⁺ eff	g N/m ³	1.0	1.0	1.0	1.0
NO ₃ ⁻ eff	g N/m ³	5.8	6.3	8.3	8.3
P _{tot} ^{eff}	g P/m ³	0.2	0.2	0.4	1.0
PO ₃₋₄	g P/m ³	0	0	0.1	0.7
V _{tot}	m ³	6,200	4,040	3,190	2,000

Table 5 Energy and CO₂ balances

Parameter (1)	Symbol (2)	Without presettling (3)		With presettling (4)		Relative effect ^(f) (%) (5)	
		12°C	20°C	12°C	20°C	12°C	20°C
		Primary sludge Biodegradable primary sludge	kg COD/d $\Phi_{\text{CODSS}}^{\text{pre}}$ ($\Phi_{\text{CODbio}}^{\text{pre}}$)	0	0	2,924	3,472
Inert primary sludge	($\Phi_{\text{CODine}}^{\text{pre}}$)	(0)	(0)	(1,871)	(2,222)	(+100)	(+100)
Secondary sludge	kg COD/d $\Phi_{\text{CODSS}}^{\text{exc}}$	2,472	2,186	803	370	-68	-83
Biodegradable excess sludge ^(a)	($\Phi_{\text{CODbio}}^{\text{exc}}$)	(894)	(657)	(397)	(210)	(-56)	(-68)
Inert excess sludge	($\Phi_{\text{CODine}}^{\text{exc}}$)	(1,578)	(1,529)	(406)	(160)	(-74)	(-90)
Digested sludge ^(b)	kg SS/d $\Phi_{\text{SS}}^{\text{dig}}$	1,615	1,570	1,487	1,437	(-8)	(-8)
Energy consumption	MJ/d E^{cons}	-14,090	-14,200	-10,929	-10,128	(-22)	(-29)
Aeration	(E^{aer})	(-7,466)	(-8,172)	(-4,839)	(-4,612)	(-35)	(-44)
Dewatering	(E^{dew})	(-363)	(-353)	(-335)	(-323)	(-8)	(-8)
Sludge incineration ^(c)	(E^{inci})	(-6,261)	(-5,675)	(-5,755)	(-5,193)	(-8)	(-8)
Heating of water	($E_{\text{wat}}^{\text{heat}}$)	[-2,388]	[-2,110]	[-2,198]	[-1,931]	[-8]	[-8]
Evaporation of water	($E_{\text{wat}}^{\text{evap}}$)	[-14,596]	[-14,180]	[-13,430]	[-12,979]	[-8]	[-8]
Heating of water-vapor ^(d)	($E_{\text{w-v}}^{\text{heat}}$)	[-2,035]	[-1,978]	[-1,874]	[-1,811]	[-8]	[-8]
Heating of sludge ^(d)	($E_{\text{SS}}^{\text{heat}}$)	[-484]	[-455]	[-446]	[-416]	[-8]	[-8]
Heating of air ^(d)	($E_{\text{air}}^{\text{heat}}$)	[-4,277]	[-4,021]	[-3,938]	[-3,678]	[-8]	[-8]
Heat of sludge combustion	($E_{\text{inci}}^{\text{prod}}$)	[19,897]	[19,342]	[18,320]	[17,704]	[-8]	[-8]
CH ₄ production	kg CH ₄ /d $\Phi_{\text{CH}_4}^{\text{SS-pre}}$	223	164	567	609	+154	+271
Primary sludge	($\Phi_{\text{CH}_4}^{\text{SS-pre}}$)	(0)	(0)	(468)	(556)	(+100)	(+100)
Excess sludge	($\Phi_{\text{CH}_4}^{\text{SS-exc}}$)	(223)	(164)	(99)	(53)	(-66)	(-66)
CH ₄ energy ^(e)	MJ/d E_{CH_4}	4,460	3,280	11,340	12,180	+154	+271
Net energy consumption	MJ/d E_{net}	-9,630	-10,920	411	2,052	-104	-119
Influent COD	kg COD/d $\Phi_{\text{COD}}^{\text{infl}}$	5,313	5,313	5,313	5,313	0	0
Effluent COD	kg COD/d $\Phi_{\text{COD}}^{\text{eff}}$	353	347	304	297	-14	-14
CO ₂ production	kg CO ₂ /d Φ_{CO_2}	8,144	8,330	6,830	6,615	-16	-21
Power generation	kg CO ₂ /d ($\Phi_{\text{CO}_2}^{\text{pow}}$)	(1,324)	(1,502)	(-57)	(-282)	(-104)	(-119)
COD oxidation	kg CO ₂ /d ($\Phi_{\text{CO}_2}^{\text{COD-oxi}}$)	(6,820)	(6,828)	(6,887)	(6,897)	(+1)	(+1)

(a)90% of biomass COD.

(b)Consisting of inert organic substance from primary and excess sludge ($\Phi_{\text{CODine}}^{\text{pre}}$ + $\Phi_{\text{CODine}}^{\text{exc}}$) and poly-P in PAOs (X_{pp}).

(c) $E_{\text{inci}} = E_{\text{inci}}^{\text{cons}} - E_{\text{inci}}^{\text{prod}} = (E_{\text{wat}}^{\text{heat}} + E_{\text{wat}}^{\text{evap}} + E_{\text{w-v}}^{\text{heat}} + E_{\text{SS}}^{\text{heat}} + E_{\text{air}}^{\text{heat}}) \times (1 + \delta_E) - [\Phi_{\text{SS}}^{\text{dig}} \times (1 - f_{\text{ash}}^{\text{dig}}) \times \Delta H_{\text{SS}}]$
(van Loosdrecht *et al.*, 1997).

(d)Up to 250°C.

(e) $E_{\text{CH}_4} = \Phi_{\text{CH}_4}^{\text{SS}} \times \eta \times \Delta H_{\text{CH}_4}$; $\eta = 0.4$, power generation efficiency by CH₄ combustion; $\Delta H_{\text{CH}_4} = 50\text{MJ/kg}$, heat of CH₄ combustion (Janssen, 1991).

(f)Calculated as: (Column 4 – Column 3)/Column 3 × 100%.

incineration. Due to a slight difference on the effluent COD concentration with and without presettling, the CO₂ emission from COD oxidation results in a slight difference. Specifically, the CO₂ emission from COD oxidation is increased by 1% with presettling.

Energy consumption contributes to a significant difference on CO₂ emissions. As shown in Table 5, the CO₂ emission from power generation is reduced by 104% and 119% at 12 and 20°C, with COD presettling of 80% and 95%. In other words, the net energy consumption is reduced by 104% and 119% with presettling. This is due to two factors. First, aeration accounts for the savings of 35% and 44% on energy consumption. Secondly, CH₄ production is increased by 154% and 271% with presettling. Besides, the energy consumption on dewatering and incineration is decreased by 8%.

As a whole, the net CO₂ emissions are reduced by 16% and 21% at 12 and 20°C, with COD presettling of 80% and 95%. It is worthy of special mention that the net energy con-

sumption is positive with presettling (411 and 2,052 MJ/d at 12 and 20°C). This means that the energy produced from CH₄ is in excess after balancing the energy consumption for aeration, dewatering and incineration, which leads to an overall positive effect on the environment.

Conclusions

Contribution of P-bacteria to reduction of COD in the N removal is demonstrated for a planned WWTP with the BCFS[®] process by simulation. The overall effects of saving COD for CH₄ production on the environment are fully evaluated by the simulation results, based on mass and energy balances.

Simulation indicates that denitrifying phosphate-removing bacteria (DPB) can save 53–59% of COD for the N removal only via ordinary denitrification at 12–20°C. Due to contribution of DPB, the optimal ratios of COD/N and COD/P (based on biodegradable COD) for integrated N and P removal are determined to be 3.9–4.5 g COD/g N and 32.2–35.2 g COD/g N. This leads to an increase of CH₄ production by 154–271%, and to a reduction of net energy consumption by 104–119%. The significant energy saving mainly due to CH₄ production and aeration reduction contributes to a reduction of net CO₂ emissions by 16–21%. Energy balance with presettling clearly indicates that the energy produced from CH₄ is enough to balance that consumed in aeration, dewatering and incineration. Presettling of particulate COD make it possible to reduce the total volume of reactors by about 50%.

It is thus concluded that contribution of P-bacteria to saving COD has overall positive effects on the environment.

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