Scenario Analysis of Nutrient Removal from Municipal Wastewater by Microalgal Biofilms

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Appendix A—Additional Scenario Analysis Calculations and Parameters

1. Microalgae

Table A.1 shows the solar irradiation from May to September in the Netherlands (in Wh and MJ). As discussed in the article, 43% of this irradiation is used by the microalgae, equivalent to the photosynthetic active radiation (PAR). The summed total irradiation is therefore 1038 MJ/m^2.

To convert this amount of energy to the amount of mol photons received, first the amount of energy of a photon (e; J) is calculated using Equation A.1 and a wavelength of 550 nm to represent the average energy of a sunlight photon:

$$e = h \cdot \frac{c}{\lambda} \; [J] \tag{A.1}$$

with h Plank's constant (J·s); c the speed of light (m/s) and λ the wavelength (m).

Using Avogadro's number (N_a; mol^{-1}), the energy per mol photons (E; J/mol photons) is calculated:

$$E = e \cdot N_a \; [J/mol \;\; photons] \tag{A.2}$$

With the amount of energy per mol photons known, the solar irradiation (I_{sun}; MJ/m^2/d) is converted to mol photons/m^2/d:

$$PFD = \frac{I_{sun}}{E} \; [mol \;\; photons/m^2/d] \tag{A.3}$$

Table A.1. Solar irradiation from May to September in Leeuwarden, the Netherlands, data from [1]. The fraction of PAR (400–700 nm) within sunlight (43%) calculated based on the ASTM G173-03 spectrum of light irradiance.

Month	Solar irradiation (Wh/m^2/day)	Solar irradiation (MJ/m^2/day)	Solar irradiation PAR (43%) (MJ/m^2/day)	Solar irradiation PAR (I_{sun}) (MJ/m^2/month)	Solar irradiation PAR (PFD) (mol photons/m^2/month)
May	5005	18.0	7.7	240	1105
Jun	5021	18.1	7.8	233	1072
Jul	4895	17.6	7.6	235	1080
Aug	4179	15.0	6.5	201	922
Sep	2778	10.0	4.3	129	593
Total				(MJ/m^2)	(mol photons/m^2)
				1038	4773

Carbon dioxide Consumption

With the biomass production known, using Equation 2 or 3 in the article, the amount of CO_2 consumed is calculated, as 1 mol of biomass always requires 1 mol of CO_2.

2. Heterotrophs

2.1. Oxygen Consumption

The oxygen consumption of the sludge (R_o) consists of the oxygen requirement of the heterotrophs degrading the COD present and the nitrifiers converting NH_4^+. It is hereby assumed that the amount of biomass produced by nitrifiers and denitrifiers is negligible. The R_o is calculated according to [2]:

$$R_o = Q \cdot \left(COD_{b,in} - COD_{b,out}\right) - 1.42 \cdot P_X + 4.33 \cdot Q \cdot (N_{in} - N_{out}) - 2.86 \cdot (N_{in} - N_{out}) \quad [g/d] \tag{A.4}$$

2.2. Carbon Dioxide Production

Assuming acetate as COD the following stoichiometrical equation is used for oxidation by activated sludge:

$$5CH_3COO^- + 1NH_4^+ + 5O_2 \rightarrow C_5H_7O_2N + 3H_2O + 5CO_2 + 5OH^- \tag{A.5}$$

Equation A.5 shows that 1 mol of CO_2 is produced per mol of O_2 consumed during COD conversion. The CO_2 production (R_{CO2}) is therefore calculated as the total O_2 requirement minus the O_2 requirement of nitrification (in moles). The CO_2 consumption of nitrification is assumed to be negligible.

$$R_{co_2} = R_0 - 4.33 \cdot Q \cdot (N_{in} - N_{out}) \cdot \frac{44}{32} \; [g/d] \tag{A.6}$$

Table A.2. Symbols and parameters used in the calculations. Wastewater treatment vales from [2], mass fractions N and P microalgae from [3–5] and the quantum yield oxygen deducted from [6].

Symbol	Description	Value	Unit
λ	wavelength	$5.5 \cdot 10^{-7}$	m
A	area of microalgal biofilm system	(calculated)	m^2
c	speed of light	$2.998 \cdot 10^8$	m/s
COD_b	biologically degradable chemical oxygen demand		g/m^3
e	energy of a photon	(calculated)	J
E	energy of 1 mol of photons	(calculated)	J/mol photons
f_d	fraction remaining as cell debris	0.15	g VSS/g VSS
$f_{N,algae}$	mass fraction of nitrogen in biomass microalgae	7.8	% (g/g)
$f_{N,sludge}$	mass fraction of nitrogen in biomass sludge	12.0	% (g/g)
$f_{P,algae}$	mass fraction of phosphorus in biomass microalgae	1.4	% (g/g)
$f_{P,sludge}$	mass fraction of phosphorus in biomass sludge	2.0	% (g/g)
h	Planck's constant	$6.626 \cdot 10^{-34}$	J·s
PFD	photon flux density	(calculated)	mol photons/m^2/d
I_{sun}	sunlight irradiation	Table 1	MJ/m^2/d
k_d	decay coefficient	0.088	d^{-1}
M_{algae}	biomass weight microalgae	21.56 [1]	g/C-mol biomass
M_{sludge}	biomass weight sludge	22.6 [2]	g/C-mol biomass
N	nitrogen concentration		g/m^3

Symbol	Description	Value	Unit
N_a	Avogrado's number	$6.02 \cdot 10^{23}$	mol^{-1}
$P_{x,sludge}$	biomass production rate of sludge	(calculated)	g VSS/d
$P_{x,A,algae}$	areal biomass production rate of microalgae	(calculated)	$g/m^2/d$
Q	flow rate	13000	m^3/d
$R_{N,sludge}$	nitrogen uptake rate by sludge	(calculated)	g/d
$R_{N,A,algae}$	areal nitrogen uptake rate by microalgae	(calculated)	$g/m^2/d$
$R_{o,sludge}$	oxygen uptake by sludge	(calculated)	g/d
$R_{o,A,algae}$	areal oxygen production by microalgae	(calculated)	$mol/m^2/d$
$R_{CO2,sludge}$	carbon dioxide production by sludge	(calculated)	g/d
SRT	solids retention time		d
	SRT Scenario 1,3	12.5	d
	SRT Scenario 2	2.5	d
Y_{sludge}	biomass yield sludge	0.4	g VSS/g bCOD
QY_{O2}	quantum yield of oxygen production	0.05	mol O_2/mol photons

[1] Biomass weight calculated based on $C_1H_{1.78}O_{0.36}N_{0.12}P_{0.01}$; [2] Biomass weight calculated based on $C_1H_{1.4}O_{0.4}N_{0.2}$.

Appendix B—Anaerobic Digestion of Heterotrophic and Microalgal Biomass

The amount of energy that can be derived from anaerobic digestion of activated sludge or from both activated sludge and microalgal biomass is calculated, in order to find the possible area reduction when using this energy for artificial lighting of the microalgal biofilm system. The amount of activated sludge ($P_{x,sludge}$) and microalgal biomass produced per day have been calculated as described in the article. The activated sludge will be digested at 35 °C. The biomass production is converted to amount of COD (1.42 g O_2/g VSS) and then to energy production in the form of methane (P_E), using the methane production at 35 °C with heterotrophs ($Y_{h,CH4}$), the density of methane at 35 °C ($\rho_{CH4,\,35}$) and the energy content of methane (E_{CH4}):

$$P_E = 1.42 \cdot P_X \cdot Y_{h,CH_4} \cdot \rho_{CH_4,35} \cdot E_{CH_4}\ [kJ/d] \quad \text{(B.1)}$$

Assuming a 30% efficiency converting methane into electricity and a 30% efficiency converting energy into light, the total amount of irradiation from artificial light produced with methane (I_{CH4}) is calculated. The total percentage of area decrease (D) with this light energy can now be calculated over the desired period of five months, as follows:

$$D = \frac{I_{CH_4}}{I_{sun} \cdot A}\ [\%] \quad \text{(B.2)}$$

The amount of energy from the anaerobic digestion of microalgal biomass is calculated in a similar manner. The methane production per microalgal biomass is taken to be 100 mL/g dry weight [7], and with the energy content of methane, the amount of energy is calculated. The decrease percentage is then calculated as described in Equation B.2. The percentage reduction has been calculated for all three scenarios treating wastewater from 100,000 inhabitants and is shown in Table B.1.

Table B.1. Area requirement of a microalgal biofilm system for 100,000 inhabitants for all three scenarios (as also shown in Table 1 in the article). In addition the reduction of required area when produced activated sludge or both activated sludge and microalgal biomass is anaerobically digested, and the energy from the produced methane is converted to artificial lighting.

Scenario	Area requirement (ha)	Area reduction with biomass activated sludge (%)	Area reduction with biomass activated sludge and microalgae (%)
Scenario 1	3.2	0.69	0.79
Scenario 2	21.0	0.15	0.27
Scenario 3	7.6	0.32	0.44

Table B.2. Symbols and parameters used in the calculations. Wastewater treatment vales from [2].

Symbol	Description	Value	Unit
$\rho_{CH4,\,35}$	density methane at 35 °C	634.6	g/m^3
A	area of microalgal biofilm system	(calculated)	m^2
D	decrease of area requirement	(calculated)	%
E_{CH4}	energy content of methane	50.1	kJ/g
I_{sun}	sunlight irradiation	Table 1 Appendix A	$MJ/m^2/d$
I_{CH4}	artificial radiant flux	(calculated)	MJ/d
$Y_{h,CH4}$	methane production at 35 °C with heterotrophs	$4.0 \cdot 10^{-4}$	m^3/g COD
P_E	energy production rate methane	(calculated)	kJ/d
P_x	production rate active sludge	(calculated)	g VSS/d

Appendix C—Lipid Production form Microalgae

In the scenario analysis the microalgae were assumed to be $C_1H_{1.78}O_{0.36}N_{0.12}P_{0.01}$ with a molar weight of 21.56 g/mol (M_{algae}). To calculate the required biomass composition and C:N ratio for lipid accumulation, it was assumed the microalgae will accumulate 40% lipids in the form of triacylglycerol (TAG with C16 side chains). This lipid accumulates in addition to the original biomass. Therefore the original biomass now accounts for only 60% of the total weight. The additional weight comes from the lipid of the composition $C_1H_{1.92}O_{0.12}$ with the molar weight (M_{TAG}). Assuming 1C-mol original biomass the additional weight is calculated as follows:

$$TAG_g = \frac{40\% \cdot M_{algae}}{60\%}\ [g/mol\ original\ biomass] \quad \text{(C.1)}$$

With M_{TAG} the additional amount of C-mol TAG per original biomass (C-mol) is now calculated:

$$TAG_{mol} = \frac{TAG_g}{M_{TAG}}\ [mol/mol\ original\ biomass] \quad \text{(C.2)}$$

With the amounts of the original biomass and the additional TAG known, the new biomass composition is calculated with addition of the different components, example shown for O normalized to 1C.

$$O_{mol} = \frac{0.36 + 0.12 \times TAG_{mol}}{C_{mol}} \; [mol] \quad \text{(C.3)}$$

The new biomass composition is $C_1H_{1.85}O_{0.24}N_{0.063}P_{0.0052}$. As can be seen from this new biomass composition, the N:P ratio is still equal to 12, as it was in the original biomass, but the C:N ratio has doubled to 16 instead of 8 in the original biomass. This new biomass composition leads to new stoichiometrical reactions for microalgal growth on nitrate and ammonium. The new equations become:

$$CO_2 + 0.95H_2O + 0.063NO_3^- + 0.0052H_2PO_4^- \rightarrow CH_{1.85}O_{0.24}N_{0.063}P_{0.0052} + 1.425O_2 + 0.068OH^- \quad \text{(C.4)}$$

$$CO_2 + 0.82H_2O + 0.063NH_4^+ + 0.0052H_2PO_4^- \rightarrow CH_{1.85}O_{0.24}N_{0.063}P_{0.0052} + 1.299O_2 + 0.058H^+ \quad \text{(C.5)}$$

These new reaction equations give 1 mol of biomass (C-basis) per 1.43 mol O_2 consumed for nitrate and 1 mol of biomass per 1.30 mol of O_2 for ammonium uptake. As the amount of produced O_2 is known (Equation 1 in the article), the amount of produced biomass is calculated.

The new uptake rate of N and P can be calculated with Equation 4 in the article. The fraction of N is now 4.7% (g/g) and the fraction of P is 0.9% (g/g). With this new uptake rate the new area is calculated according to Equation 5 from the article. The new area requirement and biomass production of the three scenarios are shown in Table C.1. In Scenario 1 the area requirement and corresponding biomass production are 1.9 times as high as the area calculated originally. In Scenarios 2 and 3, the area is 2.1 times as high. This difference is accounted for by the difference in N source; nitrate in Scenario 1 and ammonium in Scenarios 2 and 3.

Table C.1. Area requirement and biomass production when using original microalgal biomass (as also shown in Table 1 and Table 3) and area requirement, biomass production, and lipid production when using biomass that has accumulated 40% lipids. Values shown for all three scenarios per person equivalent (PE) per day.

Scenario	Area requirement original (m^2/PE)	Area requirement (m^2/PE)	Biomass production original (g/PE/d)	Biomass production (g/PE/d)	Lipid production (g/PE/d)
Scenario 1	0.32	0.63	7.7	13	5.2
Scenario 2	2.10	4.37	59	99	40
Scenario 3	0.76	1.58	21	36	14

Table C.2. Symbols and parameters used in the calculations.

Symbol	Description	Value	Unit
C_{mol}	carbon		mol
M_{algae}	weight biomass microalgae	21.56 [1]	g/C-mol biomass
M_{TAG}	weight TAG	15.83 [2]	g/mol
O_{mol}	oxygen		mol
TAG_{mol}	triacylglycerol	(calculated)	mol/mol original biomass
TAG_g	triacylglycerol	(calculated)	g/mol original biomass

[1] Biomass weight calculated based on $C_1H_{1.78}O_{0.36}N_{0.12}P_{0.01}$; [2] TAG weight calculated based on $C_1H_{1.92}O_{0.12}$.

References

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