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Glocal Assessment of Integrated Wastewater Treatment and Recovery Concepts Using Partial Nitritation/Anammox and Microalgae for Environmental Impacts

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Abstract

This study explored the feasibility and estimated the environmental impacts of two novel wastewater treatment configurations. Both include combined bioflocculation and anaerobic digestion but apply different nutrient removal technologies, i.e. partial nitritation/Anammox or microalgae treatment. The feasibility of such configurations was investigated for 16 locations worldwide with respect to environmental impacts, such as net energy yield, nutrient recovery and effluent quality, CO_2 emission, and area requirements. The results quantitatively support the applicability of partial nitritation/Anammox in tropical regions and some locations in temperate regions, whereas microalgae treatment is only applicable the whole year round in tropical regions that are close to the equator line. Microalgae treatment has an advantage over the configuration with partial nitritation/Anammox with respect to aeration energy and nutrient recovery, but not with area requirements. Differential sensitivity analysis points out the dominant influence of microalgal biomass yield and wastewater nutrient concentrations on area requirements and effluent quality. This study provides initial selection criteria for worldwide feasibility and corresponding environmental impacts of these novel municipal wastewater treatment plant configurations.

Keywords: Wastewater treatment; Wastewater management; Microalgae reactor; Energy recovery; Nutrient recovery; Effluent quality

1. Introduction

Municipal wastewater is commonly treated by conventional activated sludge (CAS) systems. However, these CAS systems cannot be considered sustainable because most of the organic matter is aerobically mineralized and the treated water is not reused. Moreover, a cost-effective technology that can recover valuable nutrients, such as nitrogen (N) and phosphorus (P), from dilute wastewater streams still remains a technological challenge. Therefore, in recent years new municipal wastewater treatment plants (WWTPs), which combine treatment with recovery of these resources (Fernandez-Arevalo et al., 2017; Khiewwijit et al., 2015b; McCarty et al., 2011) were proposed. In addition, a mathematical programing based optimization framework/criteria was also developed to manage the complexity of the design problems for a new WWTP (e.g. Bozkurt et al., 2015; Hauduc et al., 2015; Chhipi-Shrestha et al., 2017a, b). Numerical simulation, based on literature information and experimental data, can be used to assess the feasibility of such novel treatment and recovery concepts. Khiewwijit et al. (2015b) used this approach to evaluate two novel WWTP configurations (Fig. 1A) that have the potential to maximize energy and phosphorus recovery under Dutch conditions. They also compared these configurations to the CAS system (Fig. 1B).

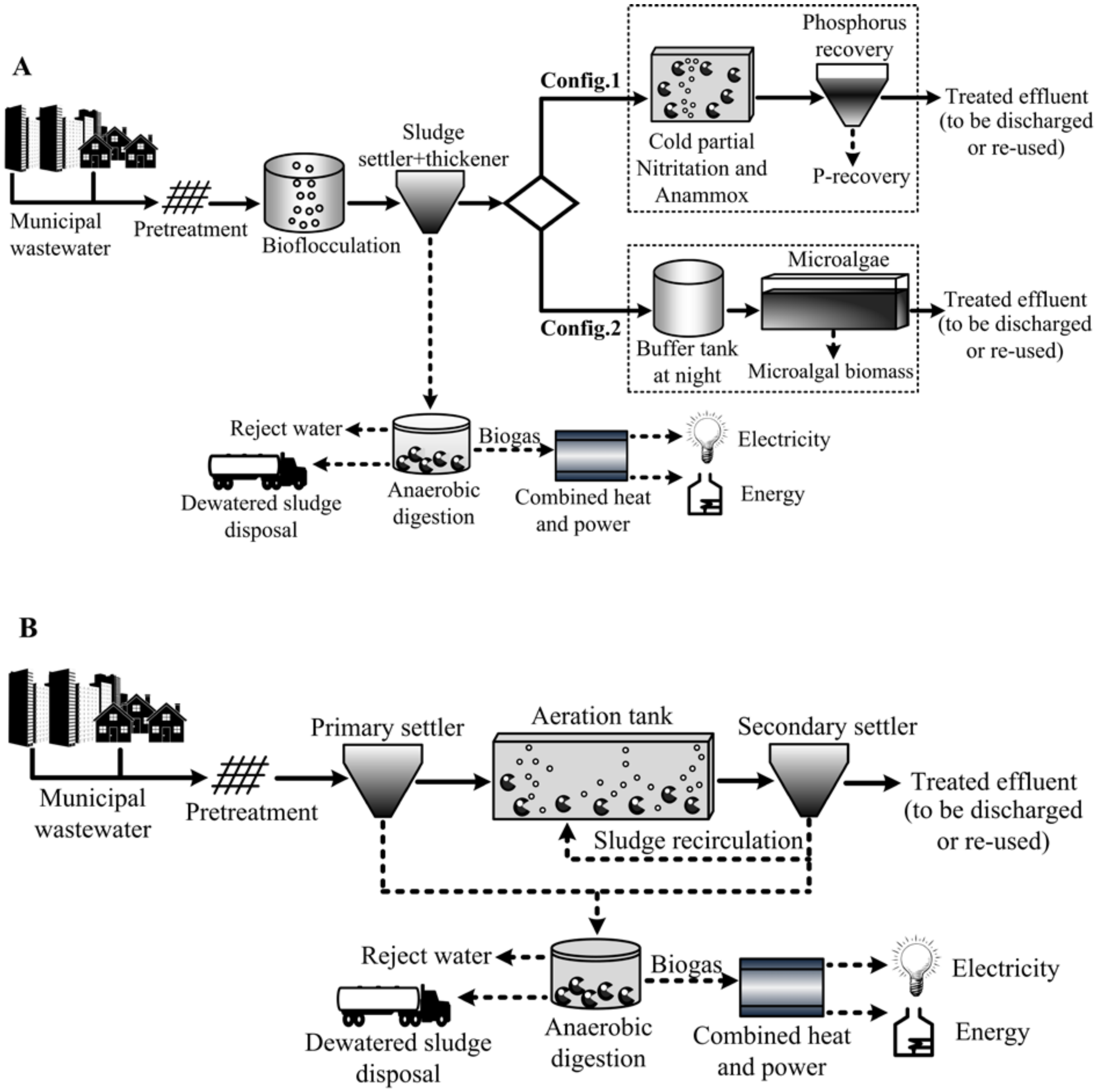

Fig. 1: (A) Two novel configurations for municipal wastewater treatment, suggested by Khiewwijit et al. (2015b), and (B) the CAS system. Solid lines indicate processes of the mainstream treatment and dashed lines indicate processes of the downstream solids treatment. ◇ is a decision block.

Given the composition of the wastewater, light intensities and temperatures at different locations around the world, each of these two configurations can be evaluated with respect to their impact on the environment. More specifically, the effluent of a WWTP with remaining N, P and chemical oxygen demand (COD) is an input to the receiving water body, e.g., a lake, river or canal, thus affecting the water quality of the surrounding environment of the WWTP (see, e.g., Wang et al., 2017). Furthermore, the CO_2 emission from the WWTP, as a result of the oxidation of organic matter in the wastewater and other steps in the wastewater treatment, contributes to greenhouse emissions (Bridle, 2007; Snip, 2010; Das, 2011; Gupta and Singh, 2012).

In this study, given the local conditions of a WWTP in terms of hydraulic and organic load, light and temperature, we aim to find a configuration that not only reduces the negative pollution effects of municipal WWTP's on the environment, but also recovers nutrients and energy to a large extent. The calculated mass and energy flows can subsequently be used as fluxes through the boundaries of a WWTP to evaluate the local effects of WWTP's on the surrounding environment.

For instance, in Configuration 1 (Fig. 1A), the diluted organic matter in municipal wastewater, after screening and grit removal, is concentrated by a bioflocculation process (Faust et al., 2014). In experiments reported by Khiewwijit et al. (2015a), it was found that bioflocculation in a high-loaded membrane bioreactor (HL-MBR) could concentrate 75.5% of the sewage COD (chemical oxygen demand), whereas only 7.5% was mineralized into CO_2. They also found that only a small fraction of the sewage NH_4-N and PO_4-P ended up in the concentrate, and 90% of these compounds was conserved in the HL-MBR permeate. The bioflocculated sewage organic matter is subsequently converted to methane in a mesophilic anaerobic digester, followed by a combined heat and power (CHP) unit to convert the methane to electricity and heat. The effluent of the bioflocculation process is subsequently treated by a (cold) partial nitritation/Anammox process for N removal. The P can be recovered, for example by struvite precipitation or by another low-cost technology (Desmidt et al., 2015). In the study of Khiewwijit et al. (2015b) it was assumed that in the near future technologies which can recover P from diluted wastewater streams will become available. It was also assumed that such technologies can remove P down to levels that meet the discharge guidelines. Bioflocculation, anaerobic sludge digestion and CHP processes are already applied in full-scale municipal WWTPs. However, more research is still required for (cold) partial nitritation/Anammox processes before it can be widely applied in practice.

In Configuration 2 (Fig. 1A), a similar approach with combined bioflocculation and anaerobic digestion of the bioflocculated organic matter is applied. However, in this configuration the nutrients N and P in the effluent of the bioflocculation process are assimilated by microalgae. A buffer tank is required to store the bioflocculation effluent during the night when there is no microalgae activity. Microalgae treatment of municipal wastewater has been extensively studied because it reduces CO_2 emission and aeration energy otherwise needed for nitrification. Furthermore, the microalgal biomass can be used as a low-cost application such as a nutrient fertilizer and complex organic substrates, or as a source for bioethanol, methane, biodiesel, and biohydrogen (Milledge and Heaven, 2014). Mahdy et al. (2015) showed the potential to produce additional biogas when sludge and microalgal biomass are co-digested.

Khiewwijit et al. (2015b) evaluated the configurations of Fig. 1A with respect to a number of key performance indicators (KPIs). It was found that Configuration 1 is the most promising configuration for the Netherlands, because it can:

1) treat wastewater year round;
2) produce an effluent at a quality that meets the discharge guidelines;
3) reduce CO_2 emission by 35% compared to the CAS system;
4) achieve a net energy yield up to 0.24 kWh per m^3 of wastewater compared to a negative net energy yield of -0.08 kWh per m^3 of wastewater for the CAS system;
5) recover 80% of the sewage P.

It was also demonstrated that Configuration 2 with microalgae treatment is not applicable in the Netherlands, because of a limited light availability, low temperature and low irradiance in the winter period. However, microalgae treatment still may be applicable in regions with a tropical climate (Olguín et al., 2003). Hence, the question is: can these findings be extrapolated on a global scale and how?

The objective of this study was, therefore, to quantitatively explore the feasibility of the above-mentioned municipal wastewater treatment configurations, including combined bioflocculation and anaerobic digestion with partial nitritation/Anammox or microalgae treatment for different locations around the globe (glocal assessment). Combined bioflocculation and anaerobic digestion, for energy saving and energy recovery, were already analyzed in detail by Khiewwijit et al. (2015b). Therefore, the present analysis mainly focused on nitrogen removal technologies, i.e. (cold) partial nitritation/Anammox in Configuration 1 and microalgae treatment in Configuration 2, and not on a comparison between different models for microalgae systems.

2. Materials and Methods

2.1. Scenario-based analysis

The Excel-based model described by Khiewwijit et al. (2015b) with conversion efficiencies and design specifications for each of the processes in Configurations 1–2 and for the reference CAS system, was used for the calculations of the mass and energy balances under steady-state conditions. A more detailed of efficiency, conversion and design parameter values used for each process in Configurations 1–2 and the reference CAS system can be found in the supplementary material. It is important to note that Khiewwijit et al. (2015b) developed a numerical Excel-based simulation tool by combining literature data and information from recent experimental research. As reported in this previous study, Configuration 2 with microalgae treatment was not feasible for a temperate climate country like the Netherlands. Therefore, the feasibility of only Configuration 1 with (cold) partial nitritation/Anammox was further explored in comparison with the reference CAS system with respect to the KPIs, i.e. effluent quality, operation applicability, CO2 emission, energy consumption/production, and net energy yield, using the Netherlands as a case study.

In the current study, the feasibility of Configuration 1 with (cold) partial nitritation/Anammox was further evaluated under different locations around the globe, as well as the feasibility of using Configuration 2 with microalgae treatment. For all configurations, it is presumed that at least 90% phosphate removal/recovery efficiency can be achieved. In Configuration 1 it is expected that such a cost-effective P recovery technology from dilute wastewater stream will become available in the near future (Desmidt et al., 2015). Therefore, in the present study cost-effective P recovery technology was not further substantiated, but was assumed to be already available. In Configurations 1–2, bioflocculation is an aerobic biological process for concentrating the sewage colloidal and suspended organic matter with the aid of extracellular polymeric substances produced by microorganisms. Aeration energy for the bioflocculation process was therefore also considered in the calculation of total energy consumption of Configuration 1 and 2. Besides, the biodegradability of organic matter from an anaerobic digester treating waste sludge in the reference CAS system was assumed to be 50% less than with bioflocculated concentrate (Bolzonella et al., 2005).

Initially, under average annual temperature and light intensity conditions in Thailand the two configurations of Fig. 1A were compared to the CAS system (Fig. 1B) with respect to the KPIs. Thailand was selected as an example of a region with tropical climates, thus having a high potential for microalgae treatment. In Thailand winter and summer conditions with respect to temperature and light intensity are similar (Table 1). Therefore, to calculate the heating energy for anaerobic digestion at 35°C, the average annual temperature was used. For calculation of the area requirement for microalgae treatment the average annual temperature and annual light intensity were used. The target N concentration in the effluent was 2.2 mg N_{total}/L, which obeys the maximum tolerable risk (MTR) guidelines used by the Dutch water boards. The P concentration in the effluent should always be below 1 mg P_{total}/L (Khiewwijit et al., 2015b).

Subsequently, a process-based model of a microalgae reactor for nutrient removal from municipal wastewater in Configuration 2 was included to explore the effects of local conditions of a WWTP with microalgae reactor on the surrounding environment. In this study, for 16 selected locations worldwide the area requirements for a microalgae reactor were estimated in relation to seasonal changes of light intensity and temperature. The most promising wastewater treatment configurations for each of these locations were identified. Wastewater characteristics and required effluent quality were the same as used in the first step.

Finally, the effects of N and P sewage concentrations, microalgal biomass yield and biomass maintenance coefficient on the area requirement of a microalgae reactor and on effluent quality were examined in more detail for those locations where microalgae treatment could possibly be applied with respect to temperature, light availability and light intensity. A sensitivity analysis with respect to temperature and wastewater characteristics on cold partial nitritation/Anammox process was already conducted by Khiewwijit et al. (2015b) and thus it was excluded in this study. Minimum and maximum values for sewage NH_4-N of 20 and 35 mg N/L were used, respectively. For PO_4-P these values were 3 and 9 mg P/L, respectively (von Sperling, 2007). In this study, a mass ratio of N and P in microalgal biomass of 5.38 g-N/g-P was used (Tuantet, 2015).

2.2. Characteristics of municipal wastewater

The treatment configurations and the CAS system were evaluated for 100,000 inhabitants (persons), which generated the average production of wastewater of 130 L/person/day, and therefore a daily load of 13,000 m^3 of wastewater was treated. Typical (average) concentrations of organic matter, NH_4-N and PO_4-P in municipal wastewater were used: 600 mg COD/L, 25 mg N/L and 5 mg P/L (von Sperling, 2007). However, it is important to note that the wastewater characteristics may vary from location to location, which caused by differences in separation of storm water, precipitation and water scarcity. Khiewwijit et al. (2015b) found that a change in total COD concentrations resulted in a significant different for the energy consumption and energy production. Hence, a sensitivity analysis with respect to wastewater characteristics will be further evaluated later in Section 2.7.

2.3. Case study for different locations worldwide

Fig. 2 shows 16 locations that were selected for the glocal assessment. To select these locations, the globe was first divided into 36 regional groups with respect to degrees of longitude and latitude, where the globe was longitude-wise divided into 6 sub-regions of 60 degrees each, and latitude-wise divided into 6 sub-regions of 30 degrees each. The final 16 regional groups were obtained after subtraction of 12 regions (polar zones), located above 60 degrees latitude North and South with an average yearly temperature below 0°C, and 8 regions of which the surface is mainly covered by ocean from the 36 regions. A representative location, i.e. a well-known city in each of the 16 regions, was then selected based on available datasets given by PV Education (2015) and IET (2015).

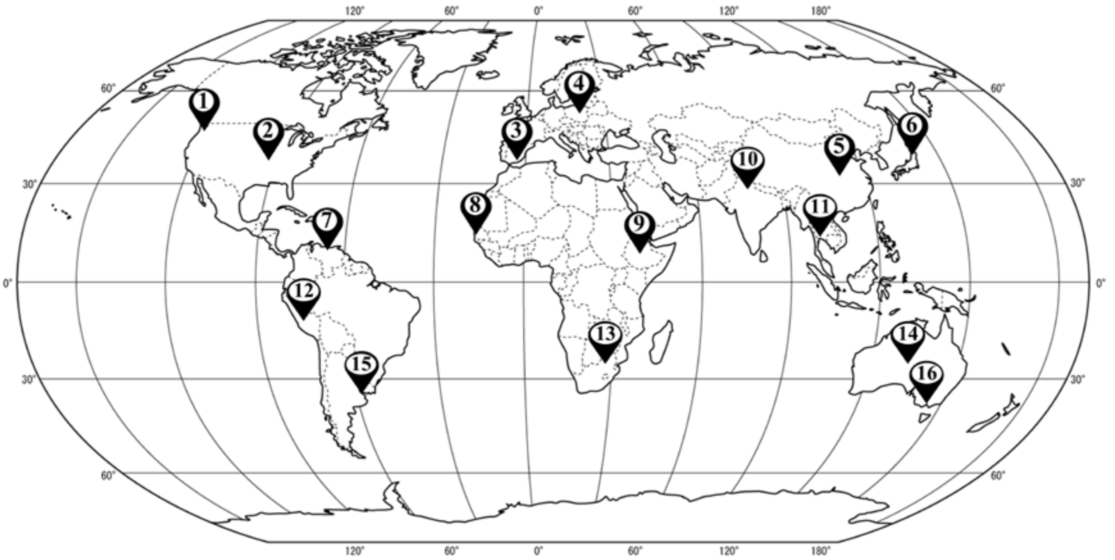

Fig. 2: Map of the 16 selected locations used in this study; (1) USA, Washington, Seattle, (2) USA, Missouri, Kansas city, (3) Spain, Almeria, (4) Poland, Warsaw, (5) China, Xi'an, (6) Japan, Akita, (7) Venezuela, Caracas, (8) Senegal, Dakar, (9) Ethiopia, Addis Ababa, (10) India, New Delhi, (11) Thailand, Bangkok, (12) Peru, Huancayo, (13) South Africa, Pretoria, (14) Australia, Alice Springs, (15) Argentina, Buenos Aries, and (16) Australia, Melbourne.

2.4. Photon flux density and temperature

Table 1 shows average annual, summer and winter values for photon flux density (PFD) and temperature for each selected location. A regional dataset of surface solar radiation was taken from PV Education (2015) and IET (2015). The PFDs were then calculated following the steps in the study of Boelee et al. (2012), where it was assumed that 43% of the average photosynthetically active radiation (PAR), that is around 550 nm (400–700 nm), is utilized by microalgae. The temperatures at each location were taken from Weatherbase (2015). The 16 locations were grouped into 3 different areas: (1) Northern hemisphere, i.e. locations above 30 degrees Northern latitude; (2) nearby the equator line; and (3) Southern hemisphere, which are locations close to and above 30 degrees Southern latitude.

Table 1

Average annual, summer and winter values of photon flux density (PFD) and temperature for the selected locations.

Country/City	PFD[a,b], mol/m²/h (μmol/m²/s)			Temperature[c], °C		
	Annual	Summer	Winter	Annual	Summer	Winter
Northern Hemisphere						
1. USA, Washington, Seattle	0.99 (275)	1.71 (475)	0.33 (91)	11.4	17.9	5.6
2. USA, Missouri, Kansas city	1.28 (354)	1.87 (520)	0.69 (192)	12.5	24.6	-0.4
3. Spain, Almeria	1.45 (402)	2.10 (583)	0.86 (240)	18.7	24.9	13.1
4. Poland, Warsaw	0.79 (220)	1.49 (414)	0.19 (52)	7.8	16.7	-0.7
5. China, Xi'an	1.15 (320)	1.50 (417)	0.80 (222)	13.4	25.7	1.0
6. Japan, Akita	0.95 (264)	1.29 (358)	0.43 (119)	11.1	22.3	0.7
Nearby Equator line						
7. Venezuela, Caracas	1.31 (363)	1.40 (389)	1.22 (339)	22.8	23.0	21.7
8. Senegal, Dakar	1.73 (481)	1.71 (476)	1.58 (438)	24.0	26.3	21.7
9. Ethiopia, Addis Ababa	1.56 (432)	1.68 (465)	1.23 (342)	16.3	17.3	15.7
10. India, New Delhi	1.32 (368)	1.59 (443)	0.98 (272)	25.0	32.6	15.2
11. Thailand Bangkok	1.56 (434)	1.78 (494)	1.77 (491)	28.2	29.0	26.3
12. Peru, Huancayo	2.04 (567)	2.22 (618)	1.93 (535)	10.1	10.9	8.9
Southern Hemisphere						
13. South Africa, Pretoria	1.62 (450)	1.93 (537)	1.30 (361)	18.6	22.7	13.0
14. Australia, Alice Springs	1.86 (518)	2.26 (628)	1.40 (388)	20.3	27.3	12.3
15. Argentina, Buenos Aries	1.37 (381)	2.00 (556)	0.74 (207)	17.7	24.0	11.6
16. Australia, Melbourne	1.18 (329)	1.87 (520)	0.57 (158)	14.3	19.3	9.3

[a] Solar radiation on the horizontal surface in kWh/m²/day taken from PV Education (2015), excluding China, Xi'an.

[b] China, Xi'an, solar irradiation on the horizontal surface in Wh/m^2/day taken from IET (2015).

[c] Temperatures taken from Weatherbase (2015).

2.5. Area requirement for microalgae

The influence of light intensity and temperature on microalgal growth has been widely explored and modeled in various ways, for example, as reviewed by Béchet et al. (2013) and reported in the studies of Béchet et al. (2017), Tuantet (2015) and Zijffers et al. (2010). However, not only the factors of light intensity and temperature that have effects on the microalgal growth, but also microalgae species, nutrient concentrations and operational parameters, such as type of photobioreactor and light-path of photobioreactor, were investigated. For instance, Tuantet (2015) developed a model to find out the biomass productivity and area requirement with respect to light intensity for (1) a high concentration of microalgal biomass cultivated on human urine, (2) a short light path photobioreactor (PBR) to minimize the dark zone and (3) *Chlorella sorokiniana* as the main microalgae species. Moreover, in this study of Tuanted (2015) the model to predict the biomass yield and biomass maintenance coefficient at different dilution rates and nutrient concentrations was also validated.

In the current study, the biomass productivity (P_{area} in g-dry weight/m^2/h) and area requirement (A in m^2/person) for a microalgae treatment reactor were calculated using the model and model parameters given in the studies of Tuantet (2015) and Zijffers et al. (2010), as shown in Eq. (1) – Eq. (5) and in Table 2. This model was chosen because it is expected that similar microalgae species and reactor design can be used for municipal wastewater treatment (Abinandan and Shanthakumar, 2015). Whereas Tuantet (2015) showed that P was the major factor limiting microalgae growth on human urine, in the current study N is the limiting nutrient, as will be shown later.

$$C_{X,N} = \frac{N_{in} - N_{eff}}{F_N} \quad \textbf{(1)}$$

$$r_{E,X} = \frac{PFD_{in}}{L * C_{X,N}} \quad \textbf{(2)}$$

$$\mu_T = (r_{E,X} - m_{E,X}) * Y_{X,E} * f_T \quad \textbf{(3)}$$

$$P_{area} = \mu_T * C_{X,N} * L \quad \textbf{(4)}$$

$$A = \frac{F_W}{L * \mu_T} \quad \textbf{(5)}$$

with $C_{X,N}$ the biomass density assuming that the amount of N rather than P determines the biomass production (g-dw/m^3), N_{in} and N_{eff} the concentrations of N in the influent and effluent, respectively (g N/m^3), F_N the fraction of N in microalgal biomass of 0.078 g-N/g microalgal biomass, $r_{E,X}$ the specific light intensity (mol photons/g-dw/h), PFD_{in} the supplied photon flux density (mol photons/m^2/h), L the light-path of photobioreactor (PBR) (m), μ_T the specific growth rate of microalgae (h^{-1}) with a temperature effect expressed by a function f_T (see below), $m_{E,X}$ the biomass maintenance coefficient (mol photons/g-dw/h), $Y_{X,E}$ the biomass yield on light energy (g-dw/mol photons), P_{area} the biomass productivity (g-dw/m^2/h), A the area requirement (m^2/person), and F_W the flow rate (m^3/h/person).

However, not only irradiance, but also temperature affects microalgae growth, as presented in Eq. (3). Fig. 3 shows the effect of temperature on growth rate of *Chlorella sorokiniana*. The effect of temperature on growth rate was calculated using the temperature function suggested by Slegers et al. (2013):

$$f_T = \left(\frac{T_{let} - T_w}{T_{let} - T_{opt}} \right)^{\beta} \exp\left(-\beta \left(\frac{T_{let} - T_w}{T_{let} - T_{opt}} - 1 \right) \right) \qquad \textbf{(6)}$$

with f_T the effect of temperature on growth rate (dimensionless), T_{let} the lethal temperature of specific microalgae species use (°C), T_{opt} the optimal growth temperature of specific microalgae species (°C), and β the curve modulating constant related to temperature coefficient Q_{10}, which is the proportional change in growth rate with a 10°C rise in temperature (dimensionless).

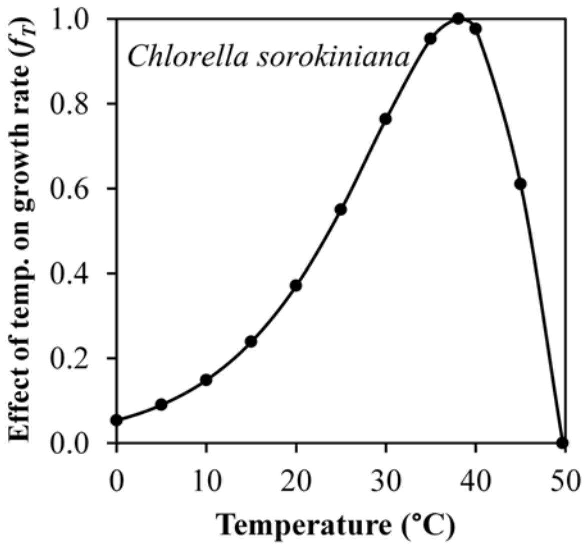

Fig. 3: Effect of temperature on growth rate of *Chlorella sorokiniana*.
If the temperature function $f_T = 0$, no growth is possible. If $f_T = 1$, growth is only influenced by light intensity, independent of temperature.

2.6. Assumptions and parameter values

The following assumptions were made: (1) wastewater temperature is equal to the air temperature; (2) the anaerobic digester is controlled at a (mesophilic) temperature of 35°C; (3) photo-inhibition of the microalgae does not take place; (4) cold partial nitritation/Anammox can be applied if the temperature is above 10°C; and (5) a change in temperature impacts both the area requirement for cultivation of microalgae and the required heating energy for anaerobic digestion. Because information on the effect of temperature on the bioflocculation is still limited, further investigation is required. Lotti et al. (2014) showed that Anammox bacteria can be enriched at a temperature of 15°C. However, based on the work of Hendrickx et al. (2014), it is expected that in the near future it will be possible to apply partial nitritation/Anammox process at temperatures as low as 10°C. The system's and microalgae dependent parameters are given in Table 2.

Table 2

Parameters used in the calculations of area requirement for cultivation of microalgae.

Parameter	Unit	Type of parameters		Reference
		System parameter	*Chlorella sorokiniana*	
N_{eff}	g N/m^3	2.2	–	Boelee et al. (2012)
$Y_{X,E}$	g-dw/mol photons	–	0.933	Tuantet (2015)
$m_{E,X}$	mol photons/g-dw/h	–	0.0068	Tuantet (2015) and Zijffers et al. (2010)
L	m	0.01	–	Tuantet (2015)
T_{opt}	°C	–	38.1	Morita et al. (2000)
T_{let}	°C	–	49.7	Morita et al. (2000)
B	(-)	–	1.6	Vona et al. (2004)

2.7. Sensitivity analysis

Differential sensitivity analysis was conducted for the area requirement of microalgae reactor in Configuration 2 with respect to two uncertain factors: the microalgal biomass yield on light energy ($Y_{X,E}$) and the microalgal biomass maintenance coefficient ($m_{E,X}$). The normalized sensitivity coefficients (dimensionless) indicate which of the two factors is most sensitive and this provides directions for future research. The normalized sensitivity coefficient for a particular independent factor was obtained by taking the partial derivatives of the dependent variable with respect to the independent factor and scaled by the nominal values of the dependent variable and independent factor. Analytical expressions for the normalized sensitivity coefficients of area (A) with respect to $Y_{X,E}$ and $m_{E,X}$ are given by (see Appendix for details):

$$S_{A,Y_{X,E}} = \frac{-F_W * \bar{Y}_{X,E}}{L * \left(\frac{PFD_{in} * F_N}{L * \left(N_{in} - N_{eff} \right)} - m_{E,X} \right) * f_T * \left(Y_{X,E} \right)^2 * \bar{A}} \quad \textbf{(7)}$$

$$S_{A,m_{E,X}} = \frac{F_W * \bar{m}_{E,X}}{L * \left(\frac{PFD_{in} * F_N}{L * \left(N_{in} - N_{eff} \right)} - m_{E,X} \right)^2 * f_T * Y_{X,E} * \bar{A}} \quad \textbf{(8)}$$

with $S_{A,Y_{X,E}}$ the nominalized sensitivity coefficient of area requirement on $Y_{X,E}$, $S_{A,m_{E,X}}$ the nominalized sensitivity coefficient of area requirement on $m_{E,X}$, $\bar{Y}_{X,E}$ the nominal value of $Y_{X,E}$, $\bar{m}_{E,X}$ the nominal value of $m_{E,X}$, and $\bar{A}$ the area requirement related to the nominal values of each factor. Based on a theoretical maximum biomass yield and the performance of *Chlorella sorokiniana* under extreme conditions (Franco et al., 2012; Kliphuis et al., 2010), the area requirements were first calculated for the nominal value of $Y_{X,E}$ and then at values of ±50 % with respect to the nominal value.

A one-at-a-time sensitivity analysis was used to quantify the changes in effluent quality and area requirement by varying sewage N and P concentrations. As mentioned before, NH_4-N concentrations varied from 20 mg N/L (N_{min}), 25 mg N/L ($N_{typical}$) to 35 mg N/L (N_{max}). PO_4-P concentrations varied from 3 mg P/L (P_{min}), 5 mg P/L ($P_{typical}$) to 9 mg P/L (P_{max}). Calculations of the microalgae reactor area requirement were performed based on average annual light intensity and temperature conditions.

3. Results and Discussion

3.1. Scenario-based analysis

The study of Khiewwijit et al. (2015b) showed that year round wastewater treatment with microalgae is not feasible in The Netherlands. Therefore, an initial quantitative scenario-based analysis of the two new WWTP configurations and the CAS system was conducted for Thailand, location 11 (Table 1) with relatively high PFD and annual temperature. Hence, it is expected that in Thailand both partial nitritation/Anammox and microalgae treatment can be applied throughout the entire year. Table 3 shows the KPIs for the three WWTP systems when operated in Thailand.

Table 3

Numerical results based on the key performance indicators (KPIs) for Configurations 1 and 2 in comparison to the CAS system, using Thailand as a case study; (A) Total energy consumption, energy production and net energy yield, (B) Nutrient recovery and CO_2 emission.

A

Configuration	Total energy consumption/production/yield (kWh/m^3 of wastewater)				
	Total energy consumption	Aeration	Heating	Energy production[a]	Net energy yield[b]
Configuration 1	0.18	0.11	0.07	0.63	0.45
Configuration 2	0.15[c]	0.03	0.07	0.63	0.48
CAS	0.36	0.29	0.07	0.20	-0.16

[a] This energy production includes both electricity and heat energy.

[b] This net energy yield is calculated based on energy consumption for aeration and heating. Energy needed for pumping, lighting and dewatering were not taken into account.

[c] This energy consumption includes also the impact of harvesting and separation of microalgal biomass on energy consumption. Assuming the harvesting step requires 0.196 kWh per kg of microalgae (Collet et al., 2011). In this study, the microalgal biomass productivity was calculated based on a fraction of N in microalgal biomass and this was 0.27 kg-dw/m^3 of wastewater.

B

Configuration	Nutrient recovery (as 100% of initial amount)		CO_2 emission/consumption (kg-CO_2/m^3 of wastewater)	
	Nitrogen	Phosphorus	CO_2 emission	CO_2 consumption
Configuration 1	0	72	0.38	0
Configuration 2	70	65	0.35	0.63[d]

CAS	0	0	0.48	0

[d] This is caused by CO_2 consumption by the microalgae.

3.1.1. Energy and nutrient recovery

While in the CAS system the major fraction of sewage organic matter is aerobically mineralized, in Configurations 1 and 2 most of this organic matter is distributed to the anaerobic digester. This explains why in Configurations 1 and 2 significantly more methane is produced, and thus more electricity and heat energy are generated than in the CAS system: 0.63 kWh per m^3 of wastewater compared to 0.20 kWh per m^3 for the CAS system (Table 3A). Table 3A also shows that for all configurations the same amount of energy was needed to heat up the anaerobic digester. In this study, the concentration of solids going to the anaerobic digester for both Configurations 1 and 2 was assumed to be the same, while the flow rate of thickener going to the anaerobic digester was assumed to be the same for all configurations. Because during bioflocculation oxidation of organic matter is minimized, the total aeration energy of Configuration 1 (0.11 kWh/m^3 of wastewater) and of Configuration 2 (0.03 kWh/m^3 of wastewater) was much lower than the aeration energy needed for the CAS system (0.29 kWh/m^3 of wastewater). The higher aeration energy in Configuration 1 compared to Configuration 2 can be explained by the oxygen that is needed for partial nitritation (Hao et al., 2002).

When applied under Thai conditions, the net energy yield of Configuration 2 (0.48 kWh/m^3 of wastewater) is slightly higher than for Configuration 1 (0.45 kWh/m^3 of wastewater), whereas a net energy deficit was found for the CAS system. It should be noted, however, that in these results energy consumption for pumping, thickening and dewatering was not taken into account, because they are only insignificant fractions of the total energy consumed during wastewater treatment when compared to energy required for aeration, heating and microalgal harvesting (Gu et al., 2017; Collet et al., 2011).

Table 3B shows that with Configuration 1 72% of the sewage P was recovered, while in the CAS system all the P and N were wasted with the excess sludge or by N_2 emission, respectively. This is because in the CAS system the sewage nutrients were removed by chemical or biological P removal process and by subsequent biological nitrification and denitrification for N removal (Khiewwijit et al., 2015b). In Configuration 2, 70% of the sewage N and 65% of the sewage P was assimilated by microalgae. This implies that Configuration 2, employing a microalgae reactor, presents a promising option for municipal wastewater treatment with respect to amounts of nutrients that can be recovered.

3.1.2. CO_2 emission

Table 3B shows that in Thailand CO_2 emission for the CAS system was 0.48 kg CO_2/m^3 of wastewater. In Configuration 1, CO_2 emission was 21% lower (0.38 kg CO_2/m^3). In Configuration 2, the CO_2 emission was 0.35 kg CO_2/m^3 of wastewater, whereas in this configuration the microalgae need 0.63 kg CO_2/m^3 for growth.

3.1.3. Area requirement

Based on the results in Table 3, Configuration 2 with microalgae treatment seems to be the most promising design for future municipal WWTPs in Thailand and in other tropical regions. However, the model calculations also show that a microalgae reactor requires an area of 2.2 m^2/person. This is similar to the 2.1 m^2/person found by Boelee et al. (2012) for a microalgae biofilm reactor that was applied for nutrient removal after a high-rate activated sludge process to remove organic pollutants. A typical CAS system requires only 0.2–0.4 m^2/person (Boelee et al., 2012), which was assumed to be the same as in Configuration 1 with (cold) partial nitritation/Anammox. Thus, microalgae treatment may only be a viable option in areas where sufficient land area is available. On larger scales, i.e. located in or nearby cities, land availability and costs may be limiting factors. This implies that microalgae treatment only would be attractive if high value products, such as carotenoids, aquaculture feed and dietary supplements can be produced by the microalgae (Enzing et al., 2014). It is recognized, however, that in this case contamination of the microalgal biomass with, for example pathogens, heavy metals and organic micropollutants that are present in the wastewater could present a serious problem.

3.2. Area requirement for different locations worldwide

The productivity of microalgae is location specific, because it is largely determined by light intensity and temperature (Slegers et al., 2013). To investigate this in more detail, microalgal biomass productivity and area requirement were calculated for the 16 selected locations around the globe, and under different seasonal conditions (Table 1).

In the Northern hemisphere, for example, Washington - Seattle, Missouri - Kansas city, Spain - Almeria, Poland - Warsaw, China - Xi'an, and Japan - Akita, biomass productivities were very different (0.2–25.5 g-dw/m^2/d) between summer and winter. The area requirement ranged between 2 and 6 m^2/person for the summer period and between 14 and 273 m^2/person for the winter period. Although the model in this study allowed microalgae growth at temperatures below 5°C, it still remains a challenge for a practical implementation at such low temperatures. Nevertheless, because of the large area requirements in the winter periods it can be concluded that Configuration 2 employing a microalgae reactor is not feasible for locations in the Northern hemisphere. De Schamphelaire and Verstraete (2009) showed that in temperate climates algae cultivation is still possible if greenhouses are applied with extra light supplied

(2-HQI 400W lamps) and high temperatures of 20–40°C. However, the considerable amount of energy required for lighting and heating can be a severe bottleneck.

In contrast, microalgae treatment seems to be applicable for locations nearby the equator line. Fig. 4 shows biomass productivity and area requirements for the six locations nearby the equator line, which are Venezuela - Caracas, Senegal - Dakar, Ethiopia - Addis Ababa, India - New Delhi, Thailand - Bangkok, and Peru - Huancayo, as a function of average annual, summer and winter conditions for temperature and light intensity.

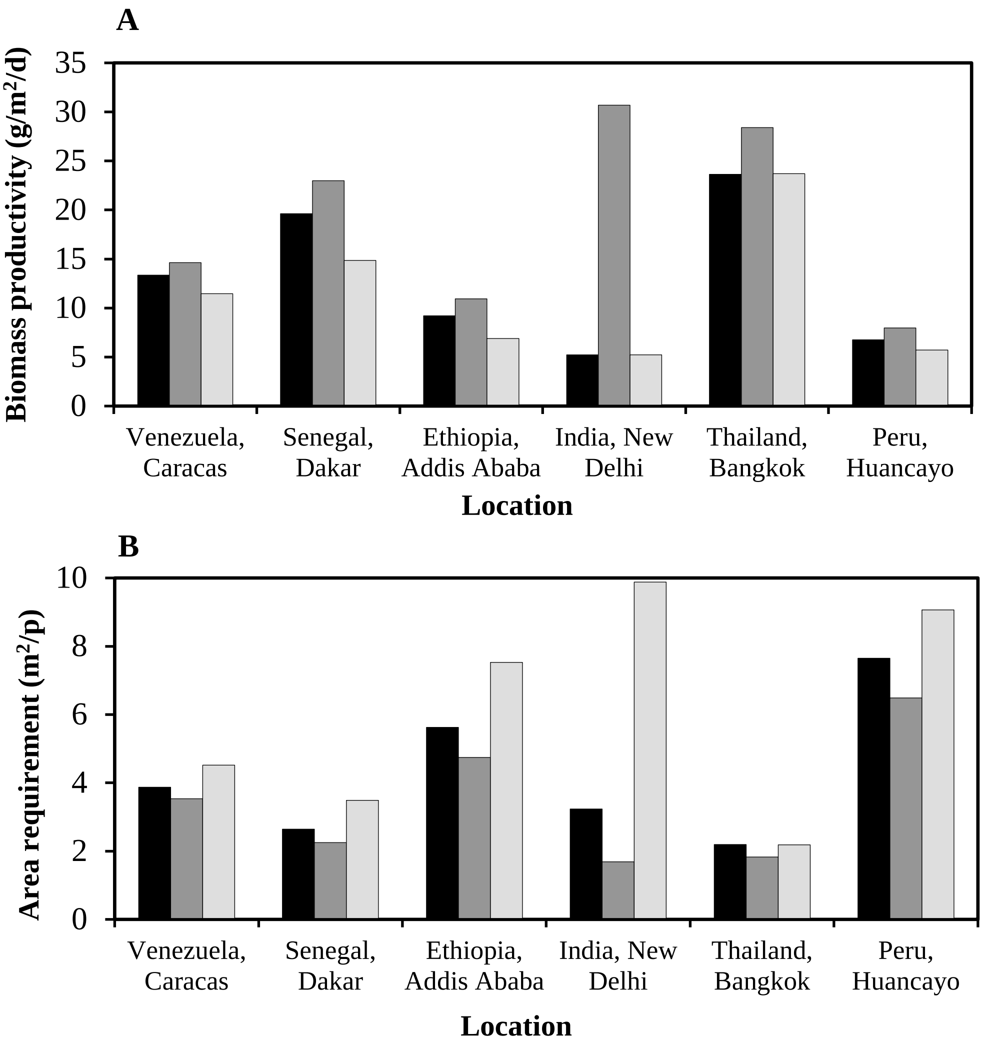

Fig. 4: Comparison of calculated (A) biomass productivity and (B) area requirements for Configuration 2 with microalgae treatment for the six locations nearby the equator line, i.e. Venezuela - Caracas, Senegal - Dakar, Ethiopia - Addis Ababa, India - New Delhi, Thailand - Bangkok, and Peru - Huancayo; (black) annual, (grey) summer, and (light grey) winter.

For the winter period, the lowest area requirement was found for Thailand - Bangkok with 2.2 m^2/person, followed by Senegal - Dakar (3.5 m^2/person), Venezuela - Caracas (4.5 m^2/person), Ethiopia - Addis Ababa (7.5 m^2/person), Peru - Huancayo (9.1 m^2/person), and India - New Delhi (9.9 m^2/person). Thus, the area requirements for configuration based on microalgae treatment always are much higher than for CAS systems (0.2–0.4 m^2/person), but are comparable to the area for other low-cost wastewater treatment systems such as vertical-flow constructed wetlands of 1.2–5.0 m^2/person and horizontal-flow constructed wetlands of 3.0–10.0 m^2/person (Dotro et al., 2017). Interestingly, the results showed that in India the area requirement in the winter period was almost 5 times higher than in the summer period (1.7 m^2/person). Thus, when winter conditions are very different from summer conditions, for instance more than a 10°C difference in temperature, microalgae treatment is only a promising option for municipal wastewater for the summer period, while the CAS system or Configuration 1 is needed for the winter period. This is probably not economically feasible and therefore Configuration 1 with (cold) partial nitritation/Anammox is the best option to treat municipal wastewater throughout the entire year.

With respect to the Southern hemisphere, microalgae treatment is only applicable for tropical regions. The area requirements for the winter period for South Africa - Pretoria and Australia - Alice Springs were 9.1 and 9.0 m^2/person, respectively. Similar to India, on these locations microalgae treatment only seems possible in the summer period, as the area requirements were 2.6 m^2/person for South Africa - Pretoria and 1.6 m^2/person for Australia - Alice Springs. In Argentina - Buenos Aries and Australia - Melbourne a microalgae treatment is not realistic, because the area requirements were as high as 18 and 30 m^2/person in the winter, respectively.

Based on the results above, it was concluded that Configuration 2 with microalgae treatment is only feasible for tropical locations, for example Venezuela - Caracas, Senegal - Dakar, Ethiopia - Addis Ababa, Thailand - Bangkok and Peru - Huancayo, where light intensity at the winter period is above 340 µmol photons/m^2/s and differences in water temperature between summer and winter are less than 5°C. Similarly, van Harmelen and Oonk (2006) suggested that microalgae cultivation is only feasible for locations between 37 degrees latitude North and South and with an average annual temperature of above 15°C. Also, in their study it was concluded that large parts of Central and Southern America, Africa and Australia are not feasible for microalgae because of a limited area. However, it is important to note that the results obtained in this study are not entirely comparable to the previous study as a different more detailed model, which includes the impact of rain and clouds, temperature and light intensity, was used in the latter study. Configuration 1 with (cold) Anammox for N removal is only feasible at locations where the winter water temperature is above 10°C (Hendrickx et al., 2014). This concerns tropical regions and some locations in temperate regions, such as Spain - Almeria, India - New Delhi, South Africa - Pretoria, Australia - Alice Springs, and Argentina - Buenos Aries. However, a technological bottleneck may be partial nitritation at low temperatures. This is because at temperatures below approximately 20°C, nitrite-oxidizing bacteria (NOB) grow faster than ammonia-oxidizing bacteria (AOB) (Hao et al., 2002). Hence, further investigation of the population dynamics of AOB for partial nitration process remains a challenge, in particular with respect to low temperatures (e.g. Giusti et al., 2011).

Fig. 5 summarizes the feasibility of applying Configuration 1 or 2 for different locations. Configurations 1 and 2 are not feasible, for example in Washington - Seattle, Missouri - Kansas city, Poland - Warsaw, China - Xi'an, Japan - Akita, and Australia - Melbourne. In these cases CAS systems should be applied, because these work throughout the entire year. It should, however, be realized that at very low water temperatures during the winter period also CAS systems may not work efficiently because of a reduced nitrification efficiency (Kim et al., 2008). However, it is important to note that a lack of experienced personal for the operation of advanced treatment technologies, such as (cold) partial nitritation/Anammox in Configuration 1 and novel P recovery in Configuration 1-2, may be a bottleneck for developing countries. Therefore, in developing countries, training programs should also be provided. Based on the results obtained in this study, it is expected that Configuration 2 with microalgae treatment requires a lower operational cost, in particular for the aeration energy, than Configuration 1 with (cold) partial nitritation/Anammox and the CAS system (Table 3A), whereas a higher maintenance cost could be found in Configuration 2 due to the microalgal harvesting (Collet et al., 2011). However, still a comparison of the overall economic feasibility of Configurations 1 Configuration 2 and the CAS system remains unclear and should be further investigated.

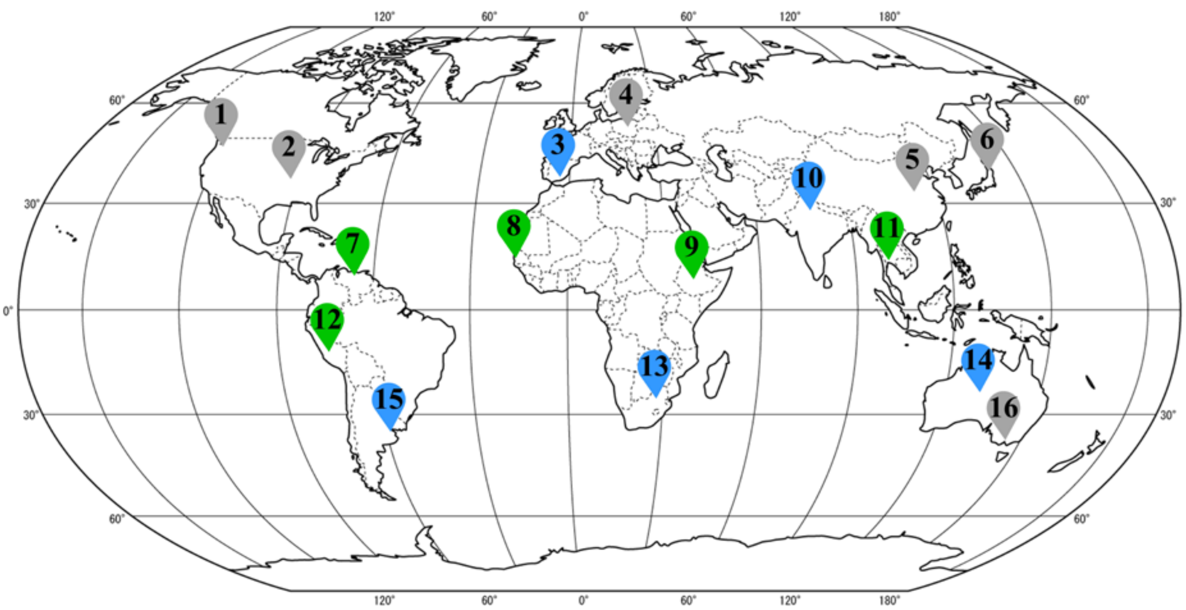

Fig. 5: Map of the 16 selected locations used in this study with the most promising candidate for municipal wastewater treatment; (blue) Configuration 1 with (cold) partial nitritation/Anammox, (green) Configuration 2 with microalgae, and (grey) the CAS system.

3.3. Sensitivity analysis

So far, for application of Configuration 2, the conclusion is that the area requirement of microalgae reactor is the bottleneck. In order to estimate the sensitivity of the area requirement with respect to wastewater composition, microalgal biomass yield and microalgal biomass maintenance, a sensitivity analysis was performed for Configuration 2. This sensitivity analysis was conducted only for Venezuela - Caracas, Senegal - Dakar, Ethiopia - Addis Ababa, Thailand - Bangkok, and Peru - Huancayo, where microalgae treatment was previously shown to be a promising treatment concept.

3.3.1. Microalgal biomass yield and maintenance coefficient

As shown in Fig. A.1–A.2 (see Appendix), the microalgal biomass yield has a major impact, while microalgal biomass maintenance has only a minor effect on the area requirements. Fig. 6 shows the effect of the yield on the area requirements for different (average) annual temperatures and light intensities.

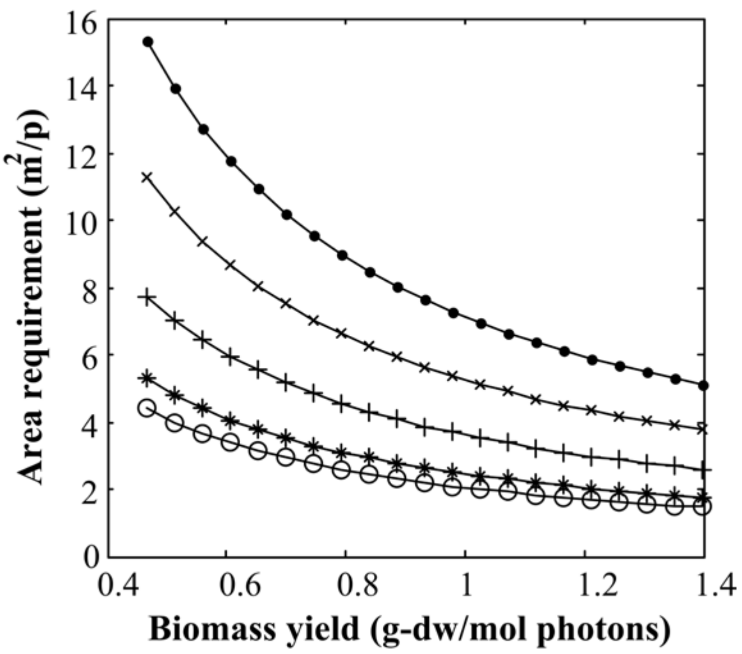

Fig. 6: Area requirements in relation to different microalgal biomass yield values for the five potential locations, that are applicable for Configuration 2 with microalgae treatment; (+) Venezuela - Caracas, (*) Senegal - Dakar, (x) Ethiopia - Addis Ababa, (○) Thailand - Bangkok, and (●) Peru - Huancayo. (Results represent the area requirement with respect to annual temperature, annual light intensity, and typical wastewater composition: 600 mg COD/L, 25 mg NH_4-N/L and 5 mg PO_4-P/L.)

Clearly, when more biomass can be grown per mole of photons, less area is needed. Kliphuis et al. (2010) reported a theoretical maximum yield on nitrate of 1.57 g-dw/mol photons. A similar value can be anticipated on ammonium as nitrogen source. In this study, a typical yield of 0.933 g-dw/mol photons was used. However, the yield depends on the microalgae species and/or reactor type (Boelee et al., 2014; Rigosi et al., 2011) and can cause huge differences in area requirements. For example, in Peru the area requirement would increase from 7.7 m^2/person at a yield of 0.933 g-dw/mol photons to almost 16 m^2/person at 0.450 g-dw/mol photons. This demonstrates that interpretation of the model results should be done with great care, and more experimental data about the biomass yield is required before conclusions can be drawn about the applicability of microalgae treatment.

Unlike the effect of biomass yield, the microalgal maintenance coefficient did not give significant differences in the area requirement (Fig. A.2). This can be explained by the low N concentrations in municipal wastewater compared to other wastewater sources. The low sewage N concentrations result in low biomass concentration (Eq. 1) and thus a large fraction of the light that is available for the microalgae (Eq. 2). Under these conditions maintenance is insignificant compared to the growth of the microalgae (Eq. 3). For example, after bioflocculation a concentration of 21 mg N/L would be assimilated by the microalgae and this would give a biomass concentration of only 0.3 g-dw/L. In contrast, other waste streams such as urine have much higher N concentrations, causing biomass densities as high as 14.2 g-dw/L (Tuantet, 2015) and under these conditions maintenance may become a significant factor.

3.3.2. Nitrogen and phosphorus concentrations in wastewater

Table 4 shows effluent quality and area requirements for a range of different concentrations of N and P (von Sperling, 2007). The numbers in boldface show that for some combinations of wastewater N and P concentrations it is impossible to achieve the required effluent concentrations of 2.2 mg N/L and 1 mg P/L, respectively with microalgae treatment and thus additional treatment is required. If the concentration of P (PO_4-P) in wastewater would increase from 5 to 9 mg P/L, N rather than P would become the limiting nutrient for microalgae growth. This implies that P would end up in the effluent with 2.78 mg P/L when the concentration of N (NH_4-N) in wastewater is at a maximum value of 35 mg N/L, and with 5.57 mg P/L when the concentration of N is at a minimum value of 20 mg N/L. Because P in the effluent can no longer meet the effluent guideline of 1 mg P_{total}/L, an additional post-treatment would be needed, e.g. slow sand filtration with iron addition. In contrast, if the concentration of N (NH_4-N) in wastewater would increase from 25 to 35 mg /L, while the concentration of P (PO_4-P) would decrease from 5 to 3 mg P/L, P rather than N becomes the limiting nutrient. This implies that N would end up as high as 20.78 mg N/L in the effluent. In this case additional N removal is required to reduce N to level that meet discharge guidelines, for example, through partial nitritation/Anammox process.

Table 4

Comparison of numerical results based on effluent quality (mg/L) and area requirement (m^2/person) for microalgae cultivation with given annual PFD and annual temperature, as mentioned in Table 1, and based on a range of sewage concentrations of NH_4-N and PO_4-P. NH_4-N concentrations varied from 20 mg N/L (N_{min}), 25 mg N/L ($N_{typical}$) and 35 mg N/L (N_{max}). PO_4-P concentrations varied from 3 mg P/L (P_{min}), 5 mg P/L ($P_{typical}$) and 9 mg P/L (P_{max}). Significant values are highlighted in bold.

Wastewater characteristic	N_{min}, P_{min}	N_{max}, P_{min}	N_{min}, P_{max}	N_{max}, P_{max}	$N_{typical}$, $P_{typical}$
Effluent quality					
NH_4-N (mg N/L)	5.64	**20.78**	2.20	2.20	2.20
PO_4-P (mg P/L)	0.15[a]	0.15[a]	**5.57**	**2.78**	0.60
Area requirement (m^2/person)					
1. Venezuela, Caracas	2.3	2.3	2.9	5.8	3.9
2. Senegal, Dakar	1.6	1.6	2.0	3.9	2.6
3. Ethiopia, Addis Ababa	3.3	3.3	4.3	8.4	5.6
4. Thailand, Bangkok	1.3	1.3	1.7	3.3	2.2
5. Peru, Huancayo	4.5	4.5	5.8	11.4	7.7

[a] P becomes the limiting nutrient; therefore, the biomass density was calculated based on a fraction of P in microalgal biomass of 0.0145 g-P/g algal biomass (Tuantet, 2015) and P-target in effluent was 0.15 mg P/L (Boelee et al., 2012).

Table 4 also shows that the composition of N (NH_4-N) and P (PO_4-P) in wastewater has a strong impact on the area requirement. The area requirement becomes about 40% lower when the concentrations of both N and P changed from typical to minimum values and approximately 50% higher when concentrations change from typical values to maximum values. At a minimum P concentration of 3 mg P/L, a higher N does not necessarily result in a higher area requirement, because P is the limiting nutrient. However, at a maximum P concentration of 9 mg P/L and a maximum N of 35 mg N/L, the cultivation area was about 2 times the area needed at a maximum P concentration and a minimum N concentration of 20 mg N/L. These results show that, in addition to light intensity and temperature, the feasibility of microalgae treatment is also strongly affected by the wastewater concentrations of N and P.

4. Conclusions

The feasibility of two novel municipal wastewater treatment configurations was investigated for 16 locations around the globe with respect to their net energy yield, N and P recovery, CO_2 emission and area requirements. The results were compared with the CAS system. Both configurations are based on combined bioflocculation and anaerobic digestion but with different nutrient removal technologies, i.e. partial nitritation/Anammox or microalgae treatment. The results quantitatively support the pre-assumption that the applicability of the two configurations is strongly location dependent. The configuration with (cold) partial nitritation/Anammox is applicable in tropical regions and some locations in temperate regions, such as Southern Europe and Southern part of South America. The configuration with microalgae treatment is only applicable the whole year round in tropical regions that are close to the equator line, such as Southeastern Asia and Northern part of South America. On the locations with low sewage temperatures, for example in Northern America and Eastern Europe, CAS systems are the only option.

Thus, to minimize the negative impacts of a wastewater treatment on its surrounding environment, a deliberate decision (depending on local conditions) must be made with respect to the technologies used in the treatment. This study provides numbers and a methodology to support the decision-making process.

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Supplementary material

Glocal Assessment of Integrated Wastewater Treatment and Recovery Concepts Using Partial Nitritation/Anammox and Microalgae for Environmental Impacts

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Appendix A—Analytical evaluation of normalized sensitivity coefficients

Analytical evaluations of the normalized sensitivity coefficients of area requirement (A) with respect to biomass yield on light energy ($Y_{X,E}$) and biomass maintenance coefficient ($m_{E,X}$) were obtained from the partial derivatives of A with respect to $Y_{X,E}$ and $m_{E,X}$, respectively. That is,

$$S_{A,Y_{X,E}} = \left(\frac{\partial A}{\partial Y_{X,E}}\right)\left(\frac{\bar{Y}_{X,E}}{\bar{A}}\right)$$

$$= \left(\frac{\partial A}{\partial \mu_T}\;\frac{\partial \mu_T}{\partial Y_{X,E}}\right)\left(\frac{\bar{Y}_{X,E}}{\bar{A}}\right)$$

$$= \left(\frac{\partial}{\partial \mu_T}\left(\frac{F_W}{L * \mu_T}\right)\;\frac{\partial}{\partial Y_{X,E}}\left[\left(r_{E,X} - m_{E,X}\right) * f_T * Y_{X,E}\right]\right)\left(\frac{\bar{Y}_{X,E}}{\bar{A}}\right)$$

$$= \left(-\frac{F_W}{L * \mu_T^{\,2}}\right)\left(\left(r_{E,X} - m_{E,X}\right) * f_T\right)\left(\frac{\bar{Y}_{X,E}}{\bar{A}}\right) \qquad \textbf{(A.1)}.$$

Substitute μ_T from Eq. (3) into Eq. (A.1), so that

$$S_{A,Y_{X,E}} = \left(\left(\frac{-F_W}{L}\right)\;\frac{1}{\left[\left(r_{E,X} - m_{E,X}\right) * Y_{X,E} * f_T\right]^2}\right)\left(\left(r_{E,X} - m_{E,X}\right) * f_T\right)\left(\frac{\bar{Y}_{X,E}}{\bar{A}}\right)$$

$$=\left(\frac{-F_W}{L}\right)\ \frac{1}{\left(r_{E,X}-m_{E,X}\right)*f_T*\left(Y_{X,E}\right)^2}\ \left(\frac{\overline{Y}_{X,E}}{\overline{A}}\right) \qquad \textbf{(A.2)}.$$

Substitute $r_{E,X}$ from Eq. (2) and subsequently $C_{X,N}$ from Eq. (1) into Eq. (A.2), leading to

$$S_{A,Y_{X,E}}=\frac{-F_W*\overline{Y}_{X,E}}{L*\left(\frac{PFD_{in}*F_N}{L*\left(N_{in}-N_{eff}\right)}-m_{E,X}\right)*f_T*\left(Y_{X,E}\right)^2*\overline{A}} \qquad \textbf{(A.3)}.$$

Similarly,

$$S_{A,m_{E,X}}=\left(\frac{\partial A}{\partial m_{E,X}}\right)\ \left(\frac{\overline{m}_{E,X}}{\overline{A}}\right)$$

$$=\left(\frac{\partial A}{\partial \mu_T}\ \ \frac{\partial \mu_T}{\partial m_{E,X}}\right)\ \left(\frac{\overline{m}_{E,X}}{\overline{A}}\right)$$

$$=\left(\frac{\partial}{\partial \mu_T}\left(\frac{F_W}{L*\mu_T}\right)\ \frac{\partial}{\partial m_{E,X}}\left[\left(r_{E,X}-m_{E,X}\right)*f_T*Y_{X,E}\right]\right)\ \left(\frac{\overline{m}_{E,X}}{\overline{A}}\right)$$

$$=\left(-\frac{F_W}{L*\mu_T{}^2}\right)\ \left(-f_T Y_{X,E}\right)\ \left(\frac{\overline{m}_{E,X}}{\overline{A}}\right) \qquad \textbf{(A.4)}.$$

Substitute μ_T from Eq. (3) into Eq. (A.4), so that

$$S_{A,m_{E,X}}=\frac{F_W*f_T Y_{X,E}*\overline{m}_{E,X}}{L*\left[\left(r_{E,X}-m_{E,X}\right)*f_T*Y_{X,E}\right]^2*\overline{A}}$$

$$=\frac{F_W*\overline{m}_{E,X}}{L*\left(r_{E,X}-m_{E,X}\right)^2*f_T*Y_{X,E}*\overline{A}} \qquad \textbf{(A.5)}.$$

Substitute $r_{E,X}$ from Eq. (2) and subsequently $C_{X,N}$ from Eq. (1) into Eq. (A.5), leading to

$$S_{A,m_{E,X}} = \frac{F_W * \overline{m}_{E,X}}{L * \left(\frac{PFD_{in} * F_N}{L * \left(N_{in} - N_{eff} \right)} - m_{E,X} \right)^2 * f_T * Y_{X,E} * \overline{A}} \quad \textbf{(A.6)}.$$

The absolute values of the normalized sensitivity coefficient of area requirement with respect to the microalgal biomass yield using Eq. (A.3) are shown in Fig. A.1 and to the microalgal biomass maintenance using Eq. (A.6) are shown in Fig. A.2.

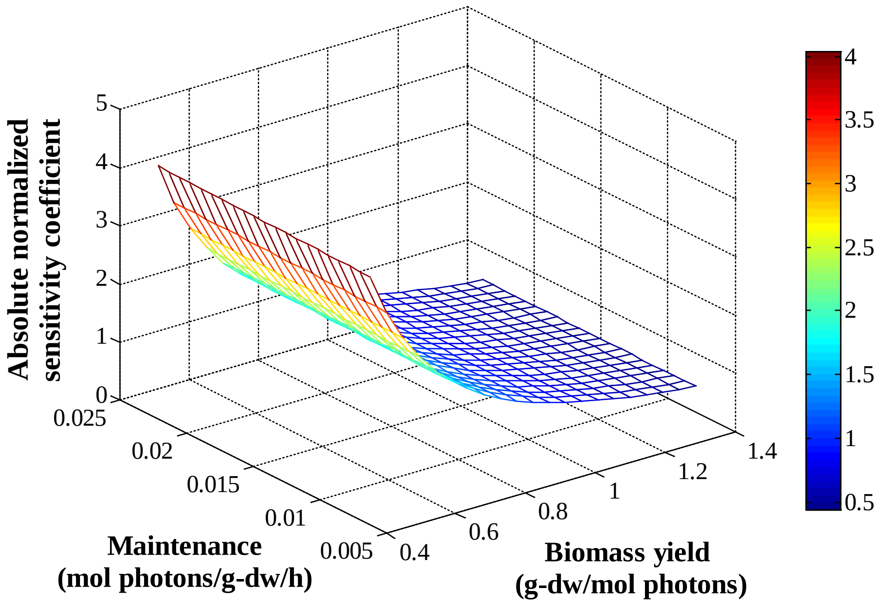

Fig. A.1: Absolute normalized sensitivity coefficient of area requirement with respect to biomass yield on light energy based on annual light intensity and annual temperature of Peru, Huancayo.

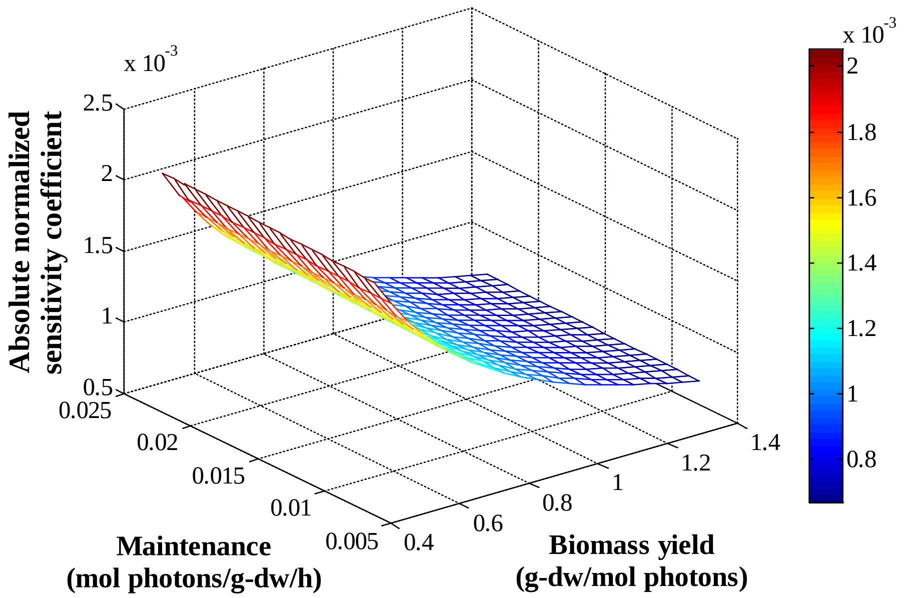

Fig. A.2: Absolute normalized sensitivity coefficient of area requirement with respect to biomass maintenance based on annual light intensity and annual temperature of Peru, Huancayo.

Appendix B—Efficiency, conversion and design parameter values used in the calculations, suggested by the study of Khiewwijit et al. (2015b)

Process	Value	Unit
Bioflocculation		
• Total COD removal efficiency	80	%CODtotal
• COD substrate need for biomass growth	40[a]	% CODbs
• O_2 need	0.51	g O_2/g $CODbs_{removed}$
• CO_2 production	0.70	g CO_2/g $CODbs_{removed}$
• Biomass yield	0.40	g VSS/g $CODbs_{removed}$
• COD in biomass	1.42	g COD/g VSS
• N in biomass	0.124	g N/g VSS
• P in biomass	0.027	g P/g VSS
• Thickener capacity	50[a]	g COD/L
Anaerobic sludge digestion		
• Total COD removal efficiency	70	% CODb
• Methane production (digestion)	0.23	g CH_4/g $COD_{removed}$
• CO_2 production	0.64	g CO_2/g $COD_{removed}$
• Biomass yield	0.058	g VSS/g $COD_{removed}$
• COD, N, P in biomass (see bioflocculation)		
Combined heat and power (CHP)		
• Electricity recovery	38	%
• Heat recovery	40	%
• Energy loss	22	%
• CO_2 production	2.75	g CO_2/g CH_4
• Enthalpy of combustion	13.9	kWh/kg CH_4
Cold partial nitritation and Anammox		
• Overall N removal efficiency	90	% NH_4^+-N
• O_2 consumption	1.95	g O_2/g NH_4^+-$N_{removed}$
• CO_2 need	0.09	g CO_2/g NH_4^+-$N_{removed}$
• N_2 production	0.885	g N_2/g NH_4^+-$N_{removed}$
• Nitrate production	0.11	g NO_3^-/g NH_4^+-$N_{removed}$
• Biomass yield (N-removal)	0.05	g VSS/g NH_4^+-$N_{removed}$
• COD in biomass	1.42	g COD/g VSS
• N in biomass	0.09	g N/g VSS
• P in biomass	0.02	g P/g VSS
• COD removal efficiency (partial nitritation)	35	% of total COD
• COD removal efficiency (Anammox)	5	% of total COD
• Conversions for COD-removal, O_2 need, CO_2 production, and COD, N, P in biomass (see bioflocculation)		
P recovery/removal		
• Overall P recovery (removal) efficiency	90[a]	% PO_4^{3-}-P
Microalgae		
• N-target in effluent	2.2	mg NH_4^+-N/L
• CO_2 need	26.19	g CO_2/ g NH_4^+-$N_{removed}$
• O_2 emissions	22.67	g O_2/g NH_4^+-$N_{removed}$

• Biomass yield	12.82	g VSS/g NH_4^+-$N_{removed}$
• COD in microalgal biomass	1.43	g COD/g VSS
• N in microalgal biomass	0.078	g N/g VSS
• P in microalgal biomass	0.014	g P/g VSS
• COD removal efficiency by heterotrophs	100[a]	% CODbs
• Conversions for COD-removal, O_2 need, CO_2 production, and concentration of COD, N, P in biomass (see bioflocculation)		
Reference CAS system		
• Total COD removal efficiency	85[a]	%
• Total N removal efficiency	90[a]	% NH_4^+-N
• Total P removal efficiency	90[a]	% PO_4^{3-}-P
• O_2 need (heterotrophs)	0.51	g O_2/g $CODb_{removed}$
• O_2 need (nitrification)	4.32	g O_2/g NH_4^+-$N_{removed}$
• O_2 need (biological P-removal)	0.49	g O_2/g $CODb_{removed}$
• CO_2 need (nitrification)	0.25	g CO_2/g NH_4^+-$N_{removed}$
• COD need (denitrification)	3.92	g COD/g NO_3^--N
• COD need (biological P)	9.06	g COD/g PO_4^{3-}-$P_{removed}$
• Biomass yield (COD-removal)	0.40	g VSS/g $CODb_{removed}$
• Biomass yield (nitrification)	0.16	g VSS/g NH_4^+-$N_{removed}$
• Biomass yield (denitrification)	0.30	g VSS/g COD_{used}
• Biomass yield (biological P)	0.37	g VSS/g COD_{used}
• COD, N, P in biomass (see bioflocculation)		
• N_2 emissions (denitrification)	0.92	g N_2/g NO_3^--N
• CO_2 emissions (heterotrophs)	0.70	g CO_2/g $CODb_{removed}$
• CO_2 emissions (biological P)	0.70	g CO_2/g $CODb_{used}$

[a] The values are based on design parameter.