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Simulation of energy balance and carbon dioxide emission for microalgae introduction in wastewater treatment plants

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ABSTRACT

A case study is described in which the activated sludge process is replaced with a microalgae-activated sludge process. The effects on the heat and electricity consumption and carbon dioxide emissions were evaluated in a system model, based on mass and energy balances of biological treatment and sludge handling process steps. Data for use in the model was gathered from three wastewater treatment plants in Sweden. The evaluation showed that the introduction of microalgae could reduce electricity and heat consumption as well as CO_2 emissions but would require large land areas. The study concludes that a 12-fold increase in the basin surface area would result in reductions of 26–35% in electricity consumption, 7–32% in heat consumption and 22–54% in carbon dioxide emissions. This process may be suitable for wastewater treatment plants in Nordic countries, where there is a higher organic load in summer than at other times of the year. During the summer period (May to August) electricity consumption was reduced by 50–68%, heat consumption was reduced by 13–63% and carbon dioxide emissions were reduced by 43–103%.

1. Introduction

The potential to develop municipal wastewater treatment methods with a resource recovery process through the capture and provision of net energy processes has been discussed in previous studies [1–3]. Concerning energy recovery from wastewater, Garrido et al. [4] concluded that, from a theoretical point of view, there is enough organic matter in the wastewater for the process to be energy self-sufficient. The energy use is dependent on the treatment method applied as well as the size of the plant and operation. Reported average values for the energy used by municipal wastewater treatment plants in different countries of the world vary between 0.30 and 0.78 kWh m^{-3} [4–6].

Most biological treatment in municipal wastewater treatment plants is based on the activated sludge process, in which air is introduced into the water by blowers to create aerobic conditions for bacteria. The aeration consumes large amounts of electricity. Panepinto et al. [7] presented a study of the energy efficiency of wastewater treatment plants in Italy. Their evaluation shows that 50% of the electricity consumption of the plant is used for the blowers. The oxygen produced by introducing microalgae into the biological process can reduce the aeration cost [8].

The cultivation of microalgae can also be used to reduce nutrients in the main wastewater stream [9] or as a treatment for nutrient-rich side streams such as reject water from sludge dewatering [10]. Algal-bacterial symbiosis systems have shown promising results with respect to nutrient removal [11,12]. The study presented in [12] found that the algal-bacterial system had a higher nutrient removal rate than the reference activated sludge system, especially at low aeration rates. At higher aeration rates the two systems showed smaller differences due to oxygen inhibiting the microalgae growth.

The microalgae can be cultivated in open raceway ponds or closed photobioreactors that can be constructed in several different ways [13,14]. The first system is simple, with low capital costs, but limited possibilities for controlling growth conditions, while the second system provides better control options but higher capital costs [15]. The cultivated microalgae are harvested from the wastewater treatment step and can then be co-digested with primary sludge from the treatment process. A drawback of a microalgae wastewater treatment system is the large land area requirements, especially by raceway ponds [8]. Most microalgae systems rely on the sun as a light source, but artificial light could also be used as an alternative [16,17]. Artificial light has the advantage that it can be tailored to the specific system, reducing the risk for photoinhibition, but it will introduce an electrical cost for the lighting.

The potential for net energy production with inclusion of microalgae was discussed by [18], based on the potential for biomass production per nutrient uptake and biomass biogas potential; however, no overall process energy balance was presented. Sturm and Lamer [19] studied the energy balance of systems with the cultivation of microalgae in open ponds for nutrient removal of effluent water from a wastewater treatment plant followed by biodiesel production from the algae and showed positive energy balances. However, the algal cultivation was

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Nomenclature

$A_{surf,reactor}$	area of the reactor surface [m^2]
BOD_{red}	amount of BOD to be reduced in the biological treatment [kg]
BOD_{in}	amount of BOD entering the biological treatment [mg L^{-1}]
BOD_{out}	amount of BOD leaving the biological treatment [mg L^{-1}]
BP_{PS}	biogas potential of the primary sludge [m^3 kg^{-1} VS]
BP_{WAS}	biogas potential of the biosludge/waste activated sludge [m^3 kg^{-1} VS]
$C_{BOD,CODb}$	factor for converting BOD to COD_b [kg COD_b kg^{-1} BOD]
C_{H2O}	heat capacity of water [kJ kg^{-1} K^{-1}]
$COD_{b,red}$	amount of biological COD to be removed in the biological treatment [kg COD_b]
$COD_{need,Pbiomass}$	COD need of the phosphorous reducing bacteria biomass [gCOD g^{-1} P removed]
$COD_{red,Pbiomass}$	COD reduced by the phosphorous reducing bacteria biomass [kg COD]
$f_{CO2,abs,per,ma}$	CO_2 absorption by microalgae [g CO_2 g^{-1} microalgae]
$f_{CO2,abs,per,nit}$	CO_2 absorption by nitrification [g CO_2 $g^{-1}$$NH_4$-N]
$f_{CO2,em,COD}$	CO_2 emission: COD/P-reducing biomass [g CO_2 g^{-1} COD]
f_{reflec}	surface reflection factor [−]
$m_{bacteria,vs}$	bacteria biomass produced [kg VS]
$m_{algae,vs}$	microalgae biomass produced [kg VS]
$m_{CO2,emission,bc}$	emission of carbon dioxide in the base case plant [kg CO_2]
$m_{CO2,emission,ma}$	emission of carbon dioxide in the plant containing microalgae [kg CO_2]
M_{O2}	molar mass of oxygen [g mol^{-1}]
$NH4\text{-}N_{red}$	amount of ammonium nitrogen to be reduced [kg]
$NH4\text{-}N_{in}$	amount of ammonium nitrogen entering the biological treatment [mg L^{-1}]
$NH4\text{-}N_{out}$	amount of ammonium nitrogen leaving the biological treatment [mg L^{-1}]
$N_{red, algae}$	amount of nitrogen reduced by the microalgae [kg NH_4-N]
$N_{uptake,algae}$	amount of nitrogen that the microalgae can uptake/reduce per unit of microalgae [g NH_4-N g^{-1} VS]
$N_{uptake,CODred,bacteria}$	amount of nitrogen that the COD_b reducing bacteria can reduce per unit of bacteria [gN g^{-1} VS]
$N_{uptakeheterobiomass}$	the amount of nitrogen take up by the COD reducing bacteria [kg N]
$O_{2,avg,algae}$	Average oxygen provided by the microalgae [kg O_2]
$O_{2,need,nitrification}$	oxygen consumed by nitrification biomass [g O_2 $g^{-1}$$NH_4$-N removed]
$O_{2,need,Pbiomass}$	oxygen needed by the phosphorous reducing bacteria [g O_2 g^{-1} COD_b removed]
$O_{2,use,CODbiomass}$	oxygen used by the COD reducing biomass [kg O_2]
$O_{2,use,nitrification}$	oxygen used by the nitrification bacteria [kg O_2]
$O_{2,use,nitrification,bc}$	oxygen used by the nitrification bacteria in the base case (without the microalgae) [kg O_2]
$O_{2,use,Pbiomass}$	the oxygen used by the phosphorous reducing bacteria [kg O_2]
$O_{2,need,remaining}$	remaining oxygen needed for the biological treatment [kg O_2]
$O_{2,use,total}$	total oxygen used/needed in the process [kg O_2]
$O_{2,use,total,bc}$	total oxygen used/needed in the process for the base case (without algae) [kg O_2]
PPD_{sun}	photosynthetic photon density [mol photons m^{-2}]
$P_{aeration,bc}$	power used for aeration in the base case [MWh]
$P_{content,biogas}$	energy content of the biogas [kWh m^{-3}]
P_{in}	amount of phosphorous entering the biological treatment [mg L^{-1}]
$P_{aeration,new}$	power used for the aeration when microalgae are utilised [MWh]
$P_{biogas,bc}$	amount of biogas in the base case in terms of power [MWh]
$P_{digester,extra}$	additional electricity required for the digestion due to the increased amount of sludge [MWh]
$P_{digester,per,m3}$	electricity consumption: anaerobic digestion treatment [kWh m^{-3} sludge]
$P_{extra,biogas}$	additional biogas in terms of power [MWh]
$P_{net,use,bc}$	net use of power in the base case [MWh]
$P_{net,use,new}$	net use of power in the microalgae case [MWh]
P_{other}	all electrical consumption at the power plant that is not for aeration [MWh]
P_{out}	amount of phosphorous leaving the biological treatment [mg L^{-1}]
$P_{uptake, algae}$	amount of phosphorous that the microalgae can uptake/reduce per unit of microalgae [g P g^{-1}VS]
P_{red}	amount of phosphorous to be reduced in the biological treatment [kg]
$P_{red, algae}$	amount of phosphorous reduced by the microalgae [kg P]
$P_{secondary,incr,algae}$	increase in power used for the secondary treatment [Mwh]
$P_{secondary,per,m3}$	electricity consumption: secondary treatment excluding aeration [kWh m^{-3} sludge]
$P_{sludge,handl,per,m3}$	electricity consumption: sludge handling [kWh m^{-3} sludge]
$P_{sludge,incr}$	additional electricity required for sludge handling due to increased amount of sludge [MWh]
$Q_{cons,bc}$	heat use in the base case [MWh]
$Q_{digester,extra}$	additional heat supplied to the digester due to increased amount of sludge [MWh]
$Q_{net,use,bc}$	net use of heat in the base case [MWh]
$Q_{net,use,new}$	net use of heat in the microalgae case [MWh]
q_{month}	wastewater flow into the biological treatment in a particular month [m^3]
SRT	sludge retention time [d]
$SumVS_{PS}$	sum of the primary sludge VS for the whole year [kg VS]
$SumVS_{WAS}$	sum of the waste activated sludge VS for the whole year [kg VS]
$T_{ambient}$	ambient temperature, assumed to be 285.15 K [K]
$T_{digester}$	digester temperature [K]
$V_{biogas,bc}$	base case biogas production for the whole year [m^3]
$V_{extrabiogas}$	amount of additional biogas due to extra sludge [m^3]
$V_{increased,sludge}$	additional sludge due to the microalgae in the system [m^3]
$V_{sludge,bc}$	amount of sludge produced from the biological treatment in the base case [m^3]
$V_{reactor}$	volume of the biological treatment basin [m^3]
$X_{algae/O2}$	microalgae biomass produced per unit of oxygen [g microalgae biomass g^{-1} O_2]
$Y_{biogas,PS}$	yield factor for the primary sludge part of all biogas [−]
Y_{obs}	yield [kg VS sludge kg^{-1}BOD]
$\gamma_{need,O2}$	minimal quanta required to liberate oxygen for sunlight [photons O_2^{-1}]
γ_{sun}	number of photons provided by the sun [mol photons]
$\eta_{electrical}$	conversion efficiency: biogas to electricity [−]
$\eta_{thermal}$	conversion efficiency: biogas to heat [−]
$\rho_{bacteria}$	concentration of bacteria biomass [kg TS m^{-3}]