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Alternative wastewater treatment process with algae (AlgA) – general mathematical model and dynamic simulation

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Abstract Conventional wastewater treatment systems are based on processes including the steps of pre-/ primary, secondary and finally the sludge treatment. In this study a treatment step with algae as an alternative secondary treatment is supposed to improve the biological nutrient removal efficiency.

In comparison with conventional technologies, less is known about the internal functioning of microalgae wastewater treatment systems. To integrate an algal system into a conventional wastewater treatment process, a mathematical model based on Activated Sludge Models (ASM) can help to understand the influences of algae on the general system of a wastewater treatment plant.

The main outcome of the present study is to apply a dynamic model for a conventional wastewater treatment plant including an integrated microalgae-bacteria model to remove the nutrients nitrogen and phosphorus. The AlgA system is simulated in SIMBA# (software for modelling and dynamic simulation in wastewater technology) considering the annual variation of environmental influences in Central Europe.

Keywords: microalgae-bacteria model; alternative wastewater treatment; dynamic simulation

1. Introduction

As an alternative to conventional wastewater treatment, the research project "Algae Biotechnology in Wastewater Treatment Plants - Phosphorus Recycling and Energy Recovery" (AlgA) is using algae in biological processes for wastewater treatment. The process is environmentally compatible and, in contrast to current process technology for phosphor elimination, does not depend on precipitation and coagulation with metal salt supplements. An important factor to consider is that algae growth is limited by light and temperature. AlgA is concerned with the factors that influence the metabolic processes of the algae and how they are based on nutrient conversion. In this type of wastewater treatment, instead of large amounts of activated sludge, biomass is now produced as a result of algal growth. The produced biomass can be separated from the wastewater and either digested in anaerobic processes to generate energy, processed into fertilizer or otherwise applied in industrial processes. The scientific understanding of the need to recycle the non-renewable resource phosphorus is increasing and is of high importance from an ecological and political point of view to minimize nutrient enrichment in water bodies and at the same time to promote independence from potential political crisis areas by avoiding purchases of phosphorus for the fertilizer industry (Mulbry et al. 2006; Pittman et al. 2011).

1.1. AlgA process technology

The pilot plant of AlgA is located at wastewater treatment plant Ober-Bessingen (WWTP OB), central Europe (Germany).

The AlgA treatment process consists of a primary settling tank with a highly loaded activated sludge system (highly loaded aeration basin) and a photobioreactor (PBR) for microalgae-bacteria processes (figure 3). The PBR is built as a high rate algae pond (HRAP) and is a variation of a wastewater treatment pond developed in California (Oswald et al. 1957). This shallow raceway pond with mechanical stirring of the mixed liquor increases microalgae biomass production and provides opportunities for low-energy wastewater treatment.

In figure 3 the model shows the process diagram with all reactor sizes and all influent values of the pilot plant visualized with SIMBA#.

1.2. Requirements for effluent

The EU Water Framework Directive 2000/60/EC (WFD) (European Commission, 2000) aims to reach a good status of water bodies. According to this aims and German Federal Government Wastewater Ordinance (AbwV, 2004) the effluent requirements in table 1 for WWTP OB are effective.

1.3. Microalgae-bacteria model

To describe the alternative wastewater treatment system based on an integrated microalgae-bacteria model, a mathematical model of the symbiotic growth of algae and bacteria is necessary. In the 80s Buhr and Miller (1983) took the potential advantages of symbiosis between algae and aerobic micro-organisms established by Oswald et al.

(1957) and presented a simple mathematical model of a high-rate algal-bacteria wastewater treatment system. They figured out the major features of process behavior. The physical, chemical and biokinetic processes for microalgae-based wastewater treatment were improved and presented in numerous models during the last decades (Wágner et al. 2016; Zambrano et al. 2016; Reichert et al. 2001; Ruiz et al. 2013; Álvarez-Díaz et al. 2017).

Solimeno combined the overall biochemical processes and simultaneous effects of light, temperature and pH in his integral mechanistic model BIO-ALGAE (Solimeno et al. 2017; Solimeno et al. 2019).

Except for the River Water Quality Model No1 (RWQM1) (Reichert et al. 2001), the integrated mechanistic is based on ASM (activated sludge model). The whole ASM “family of models” were promoted by IWA (International Water Association). Those are mathematical models to describe the processes in biological wastewater treatment based on activated sludge process including ASM1 (1987), ASM2 (1995) and 2D (1999), ASM3 (2000) (Henze et al. 2000).

However, much research in recent years has focused on integrated microalgae-bacteria wastewater treatment models. The purpose of this study is to describe and examine the implementation of this process in SIMBA# to simulate the dynamics of different components for the pilot plant located in central Germany.

The simulation offers a great opportunity to study the simultaneous effect of the climatic influences affecting microalgae and bacteria in the system. Thus allowing for the prediction of treatment efficiency and biomass production, and contributing to the system design optimization.

2. Model description

The further model description contains influence factors “influent parameter”, “temperature” and “light conditions” for the simulation. All applied data are based on the real conditions of the WWTP OB.

Influence factors are defined to describe the model. Growth kinetics, which can be expressed either in terms of biomass growth or nutrients uptake, are considering the influence of several factors such as nutrients availability and climatic influences (temperature, light availability) in central Europe (Germany).

The AlgA process is modelled and simulated in SIMBA#. All processes for algal growth were adopted from surface water quality model RWQM1 (Reichert et al. 2001) and ASM3 +bioP (Henze et al. 2000; Alex 2010).

2.1. Influent parameter

The influent has already been purified by the mechanical treatment, grit chamber and grease trap (PT). The influent concentration is based on operating data and used as steady amounts for the simulation (see table 1).

Ntot contains NH (NH4-N ammonium nitrogen + NH3-N ammonia nitrogen) and NO (NO2-N nitrite nitrogen + NO3-N nitrate nitrogen). Ptot contains PO4-P phosphate phosphorus and particulate phosphor.

The chemical oxygen demand (COD) is a wastewater characterization parameter to all the necessary information for a reliable modelling and design of biological treatment processes.

Table 1. Effluent and influent parameters WWTP OB

Pollution Parameters		**Effluent Requirement**	**Influent**
COD	chemical oxygen demand,	90 g m^{-3}	350 g m^{-3}
P_{tot}	total phosphorus	2 g m^{-3}	6 g m^{-3}
N_{tot}	total nitrogen	18 g m^{-3}	60 g m^{-3}
NH_4-N	Ammonia	10 g m^{-3}	47 g m^{-3}

2.2. Temperature

In figure 1 the ambient temperature (air) and temperature of effluent after primary treatment (PT) at WWTP OB are shown for one year. Hence the water temperature is expected to vary between 8 and 18 °C. Due to the large surface area of the PBR, the ambient temperature has a relevant influence on the processes and kinetics. The ideal growth condition for algae is between 25 and 30°C (algae_opt) (Luo et al. 2017). Consequently, a decrease factor (θalg) for algae growth should be applied (Alex 2010).

$$\theta_{alg} = e^{-0,046*(25-T)}$$

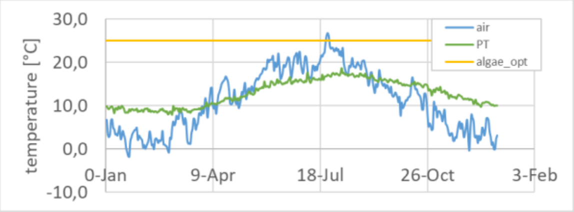

Figure 1. Temperature WWTP OB [C°]

2.2. Light

Due to the phototrophic processes of green algae for metabolism and growth processes, light is an important factor for the photosynthesis. In figure 2 the daily average light intensity shows the seasonal variation for one year measured close to the WWTP OB beginning on 1st January. The daily average light intensity varies between 0-200 W*m^{-2} (PAR) photosynthetically active radiation.

For the modelling of solar radiation, which is important for the description of algal growth, the approach from Schütze (Schütze et al. 2016) is used.

The light limitation factor caused by self-shading r(I) is the ratio of the available light intensity (I) to an ideal intensity (KI) as PAR based in Steeles approach (Steele 1962).

$$r(I) = \frac{I}{K_I} * e^{1-\frac{I}{K_I}}$$

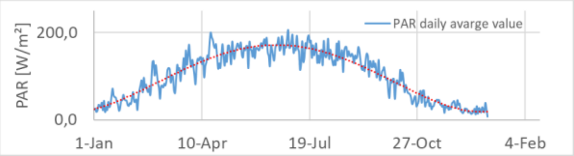

Figure 2. Light intensity WWTP OB [PAR]

2.4. Simulation settings and model components

The SIMBA model (figure 3) starts with the influent which can be simulated with either variable or constant inflow quantities and substance concentrations of COD, Nitrogen and Phosphorus. These three substances will get split up in more specific particulate and soluble components by a converter.

All reactors in the model need linked information considering temperature and light. By defining global variables constant or variable values can be linked to several basins at the same time. This is the case for the temperature and the "zero" block. The "zero" block defines the value zero and therefore operates as a switch which deactivates a process. In the aeration basin e.g., the light intensity is not considered as an important influence, because the bacterial growth is independent of light and this results in the linked value zero for light. The same principle is applied for many processes in the model.

The simulation is running for 500 days and starts in summer on 1st July to show the seasonal influence. The model uses the nomenclature of ASM models and considers 20 components - 8 dissolved and 12 particulate.

3. Results

The simulation results for the soluble components NH (ammonia and ammonium nitrogen, [g N m^{-3}]), NO (nitrate and nitrite nitrogen, [g N m^{-3}]) and PO_4 (Inorganic Phosphorus, [g P m^{-3}]) in the effluent of the WWTP and an equivalent for the biomass concentration of (H) heterotrophic biomass [g COD m^{-3}] and (ALG) algae biomass [g COD m^{-3}] in the PBR are shown in figure 4. The biomass concentrations H and ALG are presented with the factor of 0.1 for display purpose.

Particulate phosphor concentration is nearby zero at the effluent.

The values vary a lot between every month in the year caused by the dynamic changes of temperature and light intensity in the simulation.

By comparing the parameter concentrations in the effluent with the effluent requirements (table 1) it becomes obvious that the values of phosphorous in the summer months adhere to the requirements (P_{tot}<2 g P m^{-3}). The simulation shows that the nitrogen concentration does not fulfil the requirements at any time (N_{tot}>18 g N m^{-3}). During the winter all the values exceed the allowed concentrations.

The biomass concentrations (ALG and H) increase during summer and decrease during the cold period.

Responsible for the varying concentrations in the effluent is the changing amount of organisms in the PBR which transform the nutrients to biomass and therefore clean the water (figure 4, July – October). The substance concentrations are affected as well as the biomass by the changing influences and decline a lot during the winter (figure 4, November – June). During the summer algae are the dominating organism in the PBR (figure 4, ALG) due to high light intensities and temperatures. Hence a major part of the cleaning process depends on them. This changes in the winter when the bacteria biomass (H) dominates the reactor. Even though there is almost no water treatment due to low temperatures and light intensity.

4. Discussion

This simulation serves as a first impression of the strengths and weaknesses of wastewater treatment by algae and bacteria in Central Europe. There are more variables to consider when it comes to a precise prediction of biomass growth. The current model does not mention the impact of pH and CO_2 concentration. Prospectively an optimization of the ASM, more accurate parameters and probable changes in the setup of the treatment are the next research steps. Considerable change in the setup is a denitrification step to remove more of the SNO.

The model is based on ASM3 and fits into the ASM model family. Further research is needed to describe the complex interaction in mixed algal-bacterial system. Calibration and validation must be conducted with experimental data from the pilot plant receiving real wastewater.

5. Acknowledgement

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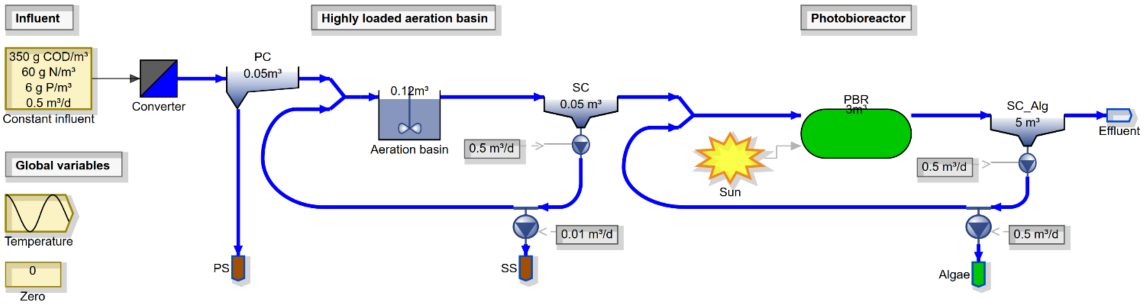

Figure 3. Process diagram AlgA pilot plant, visualized with SIMBA#

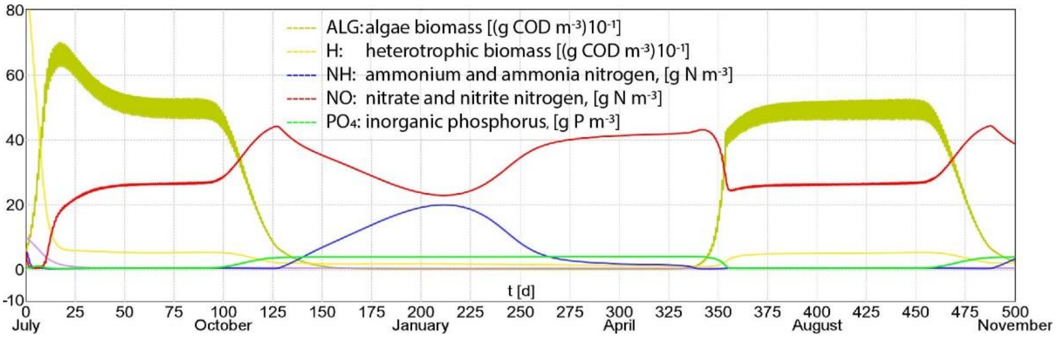

Figure 4. Simulation results of heterotrophic biomass H [(g COD m^{-3})10^{-1}] and algae biomass ALG [(g COD m^{-3})10^{-1}] concentration in the system and effluent concentration of NH, NO, PO_4-P [g m^{-3}]

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