Evaluation of the microalgae-based activated sludge (MAAS) process for municipal wastewater treatment on pilot scale

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Abstract: The microalgae-based activated sludge (MAAS) process was evaluated regarding the removal efficiency of organic matter and nitrogen from physiochemically pretreated municipal wastewater at different hydraulic retention time (HRT) on pilot scale. Additionally, the interplay between the algal and bacterial consortium was evaluated regarding the ability of the algal consortium to provide oxygen for bacterial oxidation processes. The results showed in general high organic matter (COD removal 75-90%) and total nitrogen (40-50%) removal at all HRTs (6, 4 and 2 days). The dissolved oxygen (DO) concentration was maintained stable at 6 days (6.04±0.47 mg L^{-1}) and 4 days (4.24±0.62 mg L^{-1}) HRT. However, the DO significantly declined at 2 days HRT due to loss of biomass at the high influent flow in the sedimentation unit. Nevertheless, the MAAS process functioned as a symbiotic algal-bacterial system with bacterial organic matter oxidation and nitrification and algal nutrient removal.

Keywords: Microalgae; activated sludge; municipal wastewater; pilot plant

Introduction

Most cities around the world rely on the activated sludge process as biological treatment to remove organic matter from wastewater under constant energy supply. The energy consumption for the aeration of the process alone accounts for 50-75% of the total energy used in wastewater treatment plants (WWTP) (Åmand et al., 2013). Moreover, nutrient removal in the activated sludge process is in case of nitrogen sensitive to operational changes (Kim et al., 2011) or in case of phosphorous inefficient requirring further treatment such as chemical precipitation.

In symbiotic algal-bacterial wastewater treatment processes phototrophic microalgae release oxygen, which is utilized *in situ* by bacteria to oxidize biodegradable organic compounds into CO_2 (Oswald and Gotaas, 1957). The CO_2, as well as nitrogen and phosphorous, is taken up by the microalgae for biomass formation during photosynthetic growth. Recently, high-rate algae ponds (HRAP) are transferred to full scale application to demonstrate the treatment efficiency of microalgae-based wastewater treatment for various influents (Alcántara et al., 2015; Muñoz and Guieysse, 2006). However, HRAPs require large treatment areas and are characterized by high water evaporation losses (up of 15 L m^{-2} d^{-1}) due to the low depth (max. 0.3 m) and high hydraulic retention time (HRT, min. 1.3 d from organic pollutant perspective; min. 7.5 days from a nutrient removal perspective) (Posadas et al., 2015).

To combine the benefits from both the activated sludge process and microalgae-based wastewater treatment we propose the microalgae-based activated sludge (MAAS) process. In comparison to HRAPs, the MAAS pilot is operated at higher depth (min. 0.6 m) and settled biomass depending on the desired sludge age is recycled to the system. However, the MAAS process is operated at lower mixed liquor concentration than the activated sludge process to reduce light limitation in the system. During the present study the MAAS process was evaluated regarding the wastewater treatment efficiency in continuous operation on pilot scale at different hydraulic retention time (HRT). The main focus was on the removal of organic matter and nitrogen influent and on the interplay between the bacterial and algal consortium in the system with evaluation of the pH-value and dissolved oxygen concentration as indicator for algal and bacterial activity.

Material and Methods

The microalgae-based activated sludge (MAAS) process was operated and evaluated with continuous wastewater influent on pilot scale.

Schematic setup and description of the pilot plant

The schematic setup of the MAAS process is shown in Fig. 1. The pilot plant consisted of a stainless steel tank (reactor) with an active volume of 1.1 m^3 corresponding to a height of 0.61 m of the volume placed in a freight container. The reactor was divided into 4 equal zones, each equipped with two LED lamps inducing an irradiance of 300 PAR (photosynthetically active radiation) at the water surface below the center of the lamps (Work lamp 50 W, Co/Tech, Sweden) and one agitator (Turbo-Mixer type KR 120, Turbo-Mixer Ltd., Germany). The influent had to pass all 4 zones before leaving the reactor to the sedimentation tank (0.4 m diameter, 0.025 m^3). Sedimented biomass was either returned to the reactor or taken out (excess sludge). All water and sludge flows were regulated in a continuous mode by peristaltic pumps.

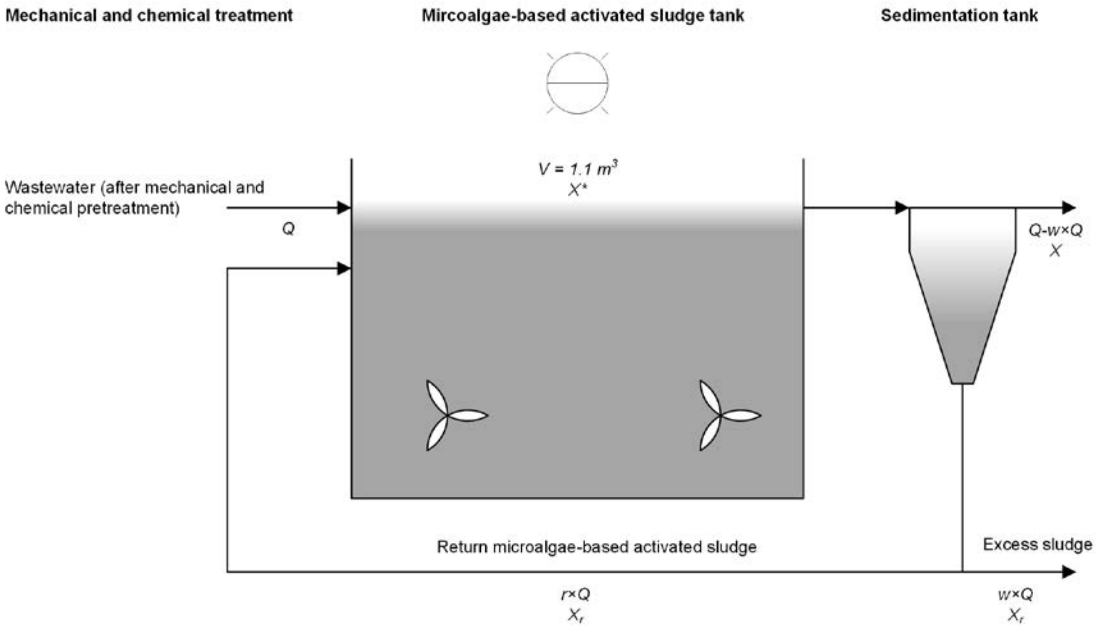

Figure 1 Schematic setup of the microalgae-based activated sludge (MAAS) pilot plant. Q=discharge rate, w=ratio of excess sludge to discharge rate, r=ratio of return sludge to discharge rate, X*=total suspended solids in MAAS tank, X=total suspended solids in effluent, X_r=total suspended solids in return sludge.

Operational parameters

The MAAS pilot system was in total operated for 240 days. The MAAS process was initially inoculated with a pre-culture of indigenous mixed algae from a lake water sample (Lake Mälaren, Sweden) grown on pre-sedimented wastewater. The focus presented in this study however was on a period with gradual decrease of the hydraulic retention time (HRT) from 6 to 4 and 2 days, respectively. The period with 6 days HRT was operated for 2 HRTs, 4 days for 3 HRTs and 2 days HRT was operated for 2 HRTs. The initial sludge retention time (SRT) was 15 days based on equation 1 and as as shown in Fig. 1:

$$SRT = (V \cdot X^*)/((w \cdot Q \cdot X_r)+(Q-w \cdot Q) \cdot X) \quad [1],$$

with V as the volume of the reactor (in L), X* as the total suspended solid concentration (TSS) in the reactor (in mg L^{-1}), w as the ratio of excess sludge rate and discharge rate, Q as the discharge rate (in L d^{-1}), X_r as the TSS of the sedimented sludge (in mg L^{-1}) and X as the TSS of the effluent from the sedimentation unit (in mg L^{-1}).

The initial ratio of excess sludge rate and discharge rate (w) was 0.15 and the ratio of return sludge rate and discharge rate (r) was 1.5±0.1 during the experimental period. The study took place during Swedish winter conditions with an average temperature of 14.6±1.1°C in the reactor. The pilot plant was located at the municipal wastewater plant in Västerås, Sweden. The municipal wastewater was pumped directly from the outflow of the presedimentation tank after mechanical and chemical ($FeSO_4$ precipitation) pretreatment. In order to avoid limitation of algal growth due to phosphate (P) deficiency K_2HPO_4 was supplemented corresponding to 3 mg L^{-1} of total phosphorous (TP) in the reactor (Anbalagan 2016).

Analytical procedures

Various parameters were measured in the influent, reactor and effluent, respectively. Temperature, dissolved oxygen concentration (DO, HQ 30D flexi, Hach Lange, Germany), pH-value (MC122 pH Controller, Milwaukee Instruments Inc., USA) and TSS (Multi Tracker, Cerlic Controls AB, Sweden) were analysed regularly in the reactor. The TSS was additionally determined in the return sludge and excess sludge.

Samples from the influent, reactor and effluent were taken after every HRT for TSS (APHA, 2005), COD (cuvette test LCK 414 and 614, Hach Lange, Germany), nutrients (ammonium and nitrate, FOSS FIASTAR 5000 fluid injection analysis and phosphorous, cuvette test LCK 349 and 350, Hach Lange, Germany) and chlorophyll *a* (Chl. *a*) (Bellinger and Sigee, 2011) determination. The samples were filtered using 0.45 µm glass filter (Whatman®, GF/C) for the determination of the soluble COD fractions and nutrients.

All removal efficiencies (RE in %) were calculated according to equation 2:

$$RE = (c_i-c_f)/c_i \cdot 100 \quad [2],$$

with c_i as initial concentration (total concentration) in the influent and c_f as final concentration (soluble part) in the effluent.

Results and Discussion

The MAAS process was evaluated regarding the wastewater treatment efficiency at different HRTs using physiochemically pretreated municipal wastewater in a continuously operated pilot plant. The composition of the pretreated wastewater fluctuated during the experimental period with an average total COD (tCOD) concentration of 155.7±98.8 mg L^{-1}, total nitrogen (TN) of 33.14±6.99 mg L^{-1} and total phosphorous (TP) of 2.14±1.20 mg L^{-1}. The dissolved phosphate concentration was low (0.20±0.27 mg L^{-1}) due to the chemical precipitation in the previous treatment.

A strong positive regression between TN and dissolved nitrogen (dN) suggested that 91% of the influent nitrogen was soluble (R^2=0.87) and moreover that 90% of the dN was ammonium (R^2=0.93). The nitrate concentration (NO_3-N) in the influent was lower (1.39±1.4 mg L^{-1}) with a minor proportion of about 4% of the dN. In addition, the proportion of soluble COD (sCOD) in relation to tCOD was 46% (R^2=0.85).

Figure 2 shows the development of the pH-value, the DO and the TSS (probe value) during the experimental period with decreasing HRT in the reactor. The pH-value was stable throughout the whole period between 6.5 and 6.8. In comparison to the pH-value in the influent (6.9±0.1) the value slightly decreased during the treatment in the reactor. On the contrary, the DO concentration showed a decreasing trend with decreasing HRT. Average DO concentration was 6.04±0.47, 4.24±0.62 and 0.94±0.64 mg L^{-1} for 6, 4 and 2 days HRT, respectively. This trend also followed a strong regression with increased DO concentration at higher HRT (R^2=0.92). The TSS concentration in the reactor followed a similar declining trend as the DO decreasing from 1,130 to 625 mg L^{-1} during the study. However, the TSS determination by the probe showed an overestimation of the value by a factor of 1.54 in correlation to the TSS concentration determined by drying (R^2=0.82) using collected data from the pilot operation (data not shown).

Figure 3 shows the influent and effluent COD concentration and COD removal efficiency (RE) during the gradual HRT reduction study. The RE was substantially influenced by the COD concentration in the influent with decreased RE at low COD. The amount of (easy) degradable organic molecules was probably lower when most of the influent COD was already oxidized or removed during the previous treatment steps. However, the effluent COD concentration was very stable at 34.45±8.68 mg L^{-1}. Apart from that, the RE was high ranging between 75 and 90% at all HRTs. Similar results of stable COD removal have been shown by Anbalagan et al. (2016) at semi-continuous conditions at the same HRTs.

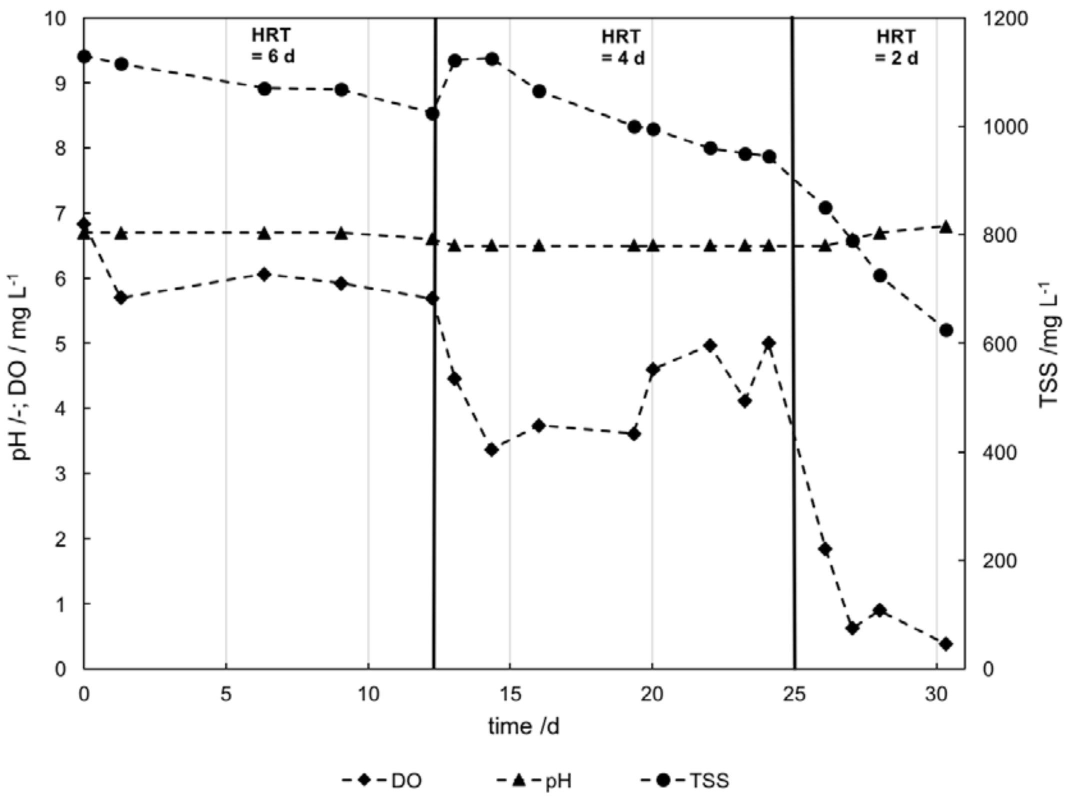

Figure 2 Development of the pH-value, dissolved oxygen (DO) and total suspended solids (TSS) concentration at 6, 4 and 2 days hydraulic retention time during continuous operation of the microalgae-based activated sludge pilot plant.

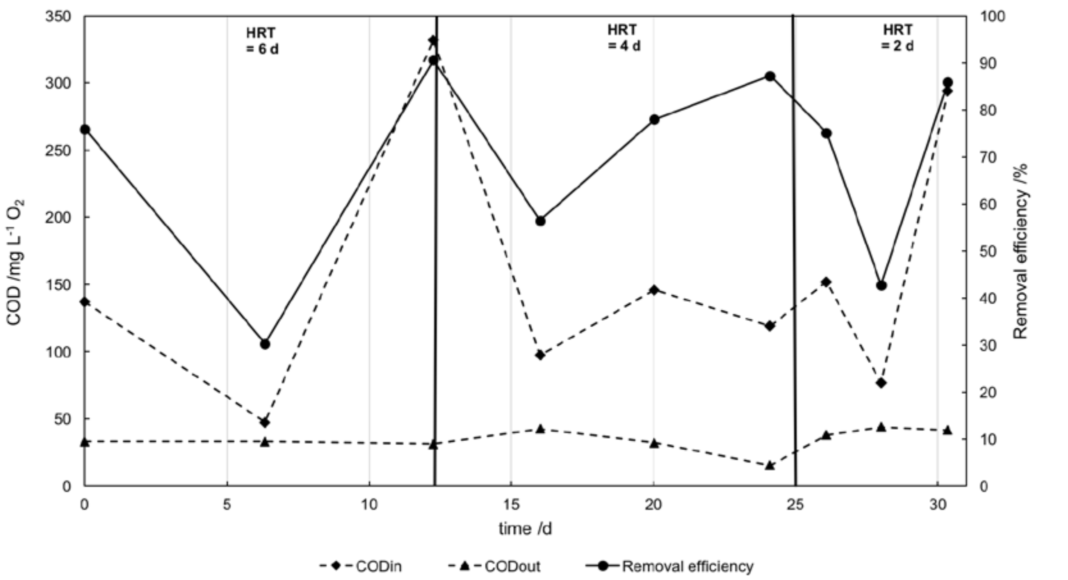

Figure 3 Development of the chemical oxygen demand (COD) in the influent (CODin) and effluent (CODout) and COD removal efficiency at 6, 4 and 2 days hydraulic retention time during continuous operation of the microalgae-based activated sludge pilot plant.

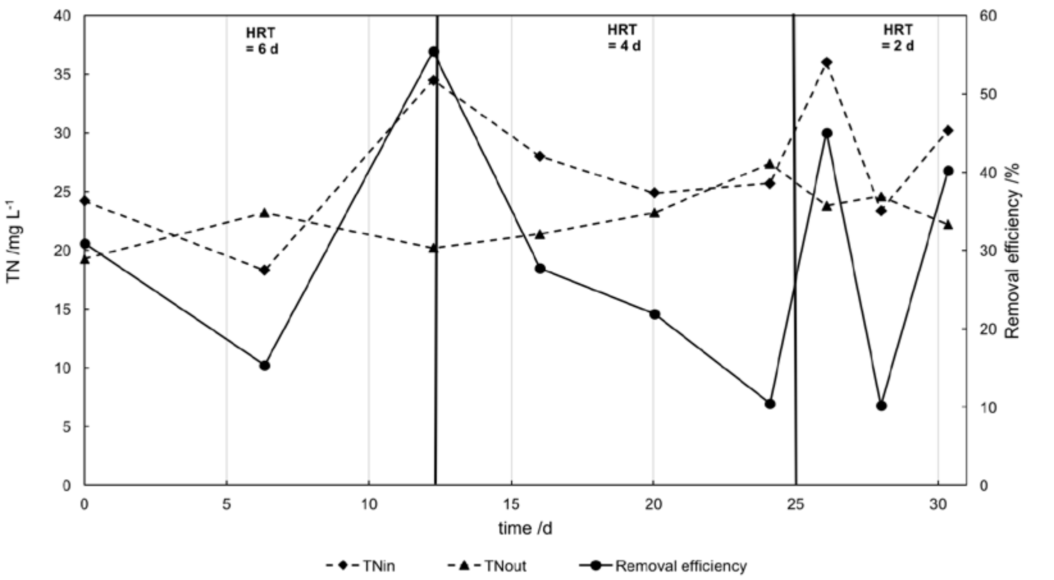

Figure 4 Development of the total nitrogen (TN) in the influent (TNin) and effluent (TNout) and TN removal efficiency at 6, 4 and 2 days hydraulic retention time during continuous operation of the microalgae-based activated sludge pilot plant.

Figure 4 shows the influent and effluent TN concentration and TN removal efficiency (RE) during the gradual HRT reduction study. The RE fluctuated with the TN concentration in the influent. When the influent concentration was higher, RE ranged between 40-50%. However, at some points the influent concentration was lower that the effluent concentration. The pilot was operated in total for 240 days and some of the dN was recycled with the return sludge and accumulated during the operation. It could be shown that between 47-90% of the effluent dN was NO_3-N. The NH_4^+ concentration in the reactor and effluent however were low (0-1.5 mg L^{-1}) during both 6 and 4 days of HRT and slightly increasing at 2 days HRT (5.8-6.9 mg L^{-1}). Krustok et al. (2016) showed that in algal-bacterial systems ammonium is oxidized by bacterial nitrification. Nitrogen, both as ammonium or nitrate, is in algae-based processes predominantly removed by cell uptake and sludge removal (Xu et al., 2014). The increasing NO_3-N concentrations at 2 days HRT indicate a reduced uptake by the algal consortium. This is supported by both the decreasing TSS and Chl. *a* content in the reactor. The Chl. *a* concentrations followed a similar trend as the TSS decreasing from 2.85 to 1.29 mg L^{-1} with a strong positive regression between both variables (R^2=0.82).

The RE of TP could not be evaluated in this study due to the chemical precipitation in the previous treatment and supplementation in the reactor. However, the RE from the reactor to the effluent was 73%, 70% and 59% at 6, 4 and 2 days HRT, respectively. Algae have distinguished sorption capacities for the removal of phosphorous (Sañudo-Wilhelmy et al., 2004). Therefore, most of the influent phosphorous could be removed with the excess sludge in an algae-based treatment system rather than precipitated by chemical addition.

The development of DO, pH, COD and NH_4^+ removal indicated that at both 6 and 4 days HRT the oxygen supply by algal photosynthesis was sufficient for both efficient bacterial oxidation of organic carbon and nitrification. However, adequate oxygen supply was crucial to maintain both processes at a stable level. At 2 days HRT oxygen supply was limited due to loss of algal biomass (as evidenced by the relationship between TSS and Chl. a) in the system. Here, TSS concentration increased in the effluent due to poor settling of the biomass in the sedimentation unit at the high flowrate during 2 days HRT. Accordingly, bacterial processes were equally affected as evidenced by increasing COD and NH_4^+ concentrations in the effluent. All in all, the bacterial processes appeared to be faster and dominant than the algal. In contrast to semi-continuous operation, where pH control by CO_2 addition had to be applied and DO concentration >10 mg L^{-1} were observed (Anbalagan et al., 2016), continuous influent induced stable O_2/CO_2 production and consumption at the respective HRT. However, the MAAS process can be described as a syntrophic bacterial-algal system, where balanced activity of both groups is required. Without photosynthetically derived O_2 no bacterial oxidation and nitrification take place. On the other hand, without CO_2 from bacterial oxidation algal photosynthesis is limited and the increasing pH reduces nutrient availability via N-stripping and P-precipitation.

Conclusions

The microalgae-based activated sludge process was operated at different hydraulic retention times with continuous influent of physiochemically pretreated wastewater on pilot scale. The MAAS process showed in general a high removal efficiency for organic matter and nitrogen. Organic matter and ammonium were degraded by bacterial oxidation and nitrification with the oxygen released by algal photosynthesis. Nitrate derived from the nitrification and CO_2 from the bacterial oxidation were utilized by the algal consortium for growth. For stable operation balanced bacterial and algal activity was required.

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