Bacteria reduction and nutrient removal in small wastewater treatment plants by an algal biofilm

G. Schumacher, T. Blume and I. Sekoulov

Technical University Hamburg-Harburg, Institute of Wastewater Management, Eissendorfer Str. 42, 21073 Hamburg, Germany (E-mail: *g.schumacher@tu-harburg.de*)

Abstract Attached algae settlement is frequently observed in effluents of wastewater treatment plants at locations with sufficient sunlight. For their growth they incorporate nutrients and the surface of the algal biofilm accumulates suspended solids from the clarified wastewater. During the photosynthesis process of algal biofilms oxygen is produced while dissolved carbon dioxide is consumed. This led to an increasing pH due to the change of the carbon dioxide equilibrium in water. The high pH causes precipitation of dissolved phosphates. Furthermore an extensive removal of faecal bacteria was observed in the presence of algae, which may be caused by the activity of algae. The experimental results indicate the high potential of these attached algae for polishing secondary effluent of wastewater treatment plants. Especially for small wastewater treatment plants a post connected stage for nutrient removal and bacteria reduction can be developed with the aid of an algal biofilm.

Keywords Algal biofilm; bacteria reduction; nitrogen removal; phosphorus removal; wastewater disinfection

Water Science and Technology **Vol 47 No 11 pp 195–202**

Introduction

Algae greatly contribute to self-purification of waters. After elimination of organic substances by bacteria, nutrients remain in waters and in the presence of sunlight the growing of algae begins inevitably. Algae consume nitrogen and phosphorus for building biomass. But in contrast to heterotrophic bacteria, algae are not dependent on an organic carbon source but on carbon dioxide. Another advantage of algae for nutrient removal is the fact that oxygen is produced in the photosynthesis process which contributes to the waters' oxygen supply (Uhlmann, 1988).

The capability of nutrient removal without an organic carbon source of algae was often used for wastewater treatment in extensive pond systems with low concentration of suspended algae or in intensive high rate algae ponds with high concentration of suspended algae. In these ponds bacteria produce CO_2 by respiration, which is used by algae for the photosynthesis process. Bacteria for the removal of carbon compounds take up oxygen from the photosynthesis. In contrast to the common treatment process for nitrogen removal, with bacteria algae fix the nitrogen in their biomass, so that the nitrogen can be retained and used as a fertilizer in agriculture. On the contrary during the nitrification/denitrification process nitrogen escapes as N_2 into the atmosphere and cannot be used any more. The disadvantage of suspended algae for the use in wastewater treatment systems is the high secondary pollution caused by algae biomass in the effluent of the ponds. This can achieve a part of 60%–90% of the effluent's BOD (Laliberté *et al*., 1994).

The problem of separation of algae and water can be avoided by using attached algae. In effluents of wastewater treatment plants at locations with sufficient sunlight these attached algae were often observed as an algal biofilm. Davis *et al*. found predominantly green algae (*Stigeoclonium, Oedogonium, Ulothrix, Scenedesmus*), blue-green algae (*Oscillatoria, Lyngbya*) and diatoms in the outlet channel of a secondary clarifier. At spots with high flow velocity only the green algae *Stigeoclonium* could be detected (Davis *et al*., 1990a). The performance of algal biofilm processes is comparable with suspended algae systems (Davis *et al.*, 1990b). The use of an algal biofilm system is especially suitable for nutrient removal. Wastewater with high organic loads impedes the development of algae, because bacteria and other microorganism will displace algae (Sládecková, 1994). A practical application for an algal biofilm process is the Algal Turf Scrubber (ATS) developed by Walter Adey and Karen Loveland which is used successfully for the treatment of waters of a very sensitive coral reef aquarium (Adey *et al.*, 1998). Investigations with domestic wastewater also showed very promising results for nutrient removal. (Craggs *et al.*, 1996).

In addition to nutrient removal a bacterial die-off was often observed in the presence of algae for example in drinking water reservoirs (Emeis, 1955) or wastewater ponds (Pearson, 1987). The first antibacterial effect of algae was already discovered in 1944 with green algae *Chlorella* (Pratt *et al.*, 1944). Anti-bacterial substances produced by algae were found, which are toxic for bacteria, especially for gram-positive bacteria (Canell Richard *et al.*, 1988). Algae create in waters a special environment with high oxygen concentration and high pH. Pearson (1987) and Curtis and Mara (1992) showed a dependence of light intensity, oxygen concentration and pH in wastewater ponds on reduction of *faecal coliforms*. Davies-Colley *et al.* (1999) described different methods of bacterial reduction caused by sunlight, high amount of dissolved oxygen and pH (produced by algae) for different kinds of bacteria. This suggests that algae have a great potential for bacterial reduction in wastewater. Investigations in a laboratory scale system showed that it was possible to reach the hygienic guidelines of the EU-Directive on Bathing Water Quality (76/160/EWG) in secondary effluent by an algal biofilm plant (Schumacher *et al.*, 1999).

In future the hygienic conditions of waters will be more important. In a proposal for a new directive the bad quality of swimming waters and the inadequate number of controlled waters in the European Union were criticised (Epades Report, 1996). The effluent of a wastewater treatment plant is not conform to these guidelines without an additional disinfection step. There are different possibilities to reduce bacteria concentrations of treated wastewaters: by physical methods using UV-radiation or microfiltration membrane, or in a chemical way oxidising bacteria with ozone or chlorine (Rudolph *et al.*, 1993). The disadvantage of physical or chemical wastewater disinfection is a high consumption of energy and material and a lot of maintenance work is necessary. For small treatment plants these processes are too costly.

A biological treatment with an algal biofilm could be a low-cost, close-to-nature alternative to the chemical and physical wastewater disinfection especially for small wastewater treatment plants. The possibility of bacteria reduction and nutrient removal for polishing small streams of wastewater was investigated in this work and a design proposal was developed.

Materials and methods

An experimental plant of 1.65 m width and 2 m length was inclined in a southern direction with an angle of 10° (Figure 1). The surface of a pressboard was covered with a plastic wrap and some side edges were fixed to prevent an outflow of the water at the sides of the board. The ground of the plant was a 0.5–1 cm thick layer of screed.

The plant was operated with the effluent of the pilot wastewater treatment plant of the TU Hamburg-Harburg in which real domestic wastewater was treated. After a short time of two weeks an algal biofilm was formed by different kinds of algae. These were mainly green algae *Ulothrix, Stigeoclonium* and *Chlamydomonas* and blue-green algae *Oscillatoria*, but also some other algae, bacteria and protozoa.

For the investigations 60 l of treated wastewater were recirculated from a stock tank over the boards by a pump. The pH (pH-meter WTW 196) and oxygen concentration (Oxi meter

WTW 196) were continuously measured. Concentrations of total phosphorus, ammonium, nitrate and nitrite taken in samples every 0.5–1 h were determined photochemically by flow injector analysers (Technicon). The efficiency of wastewater disinfection was investigated by counting indicator microorganisms occurring mainly in warm-blooded beings like faecal coliform bacteria *(E. coli)* and faecal *Streptococcus*. The determination of bacterial numbers was measured as colony forming units (CFU) according to the spatula method of four equal samples on Chromocult-Coliformen-Agar (Merck, Darmstadt) for *E. coli* and total coliform bacteria and on KF-Streptokokken-Agar (Merck, Darmstadt) for faecal *Streptococcus*.

Results and discussion

By the treatment with the algal biofilm oxygen concentration and pH increased as shown in Figure 2. After reaching the solubility equilibrium of oxygen in water, the oxygen concentration corresponded with the solar irradiance. If irradiance increased, O_2 was raised, too.

The pH reached the equilibrium point of 8.4 very fast and then pH was slowly increasing to a level of more than 10.5. When irradiance decreased, the pH remained at a constant level. The pH was influenced by the concentration of dissolved CO_2 and the carbon dioxide equilibrium in water: in the case of high CO_2 concentration the pH decreased and the pH

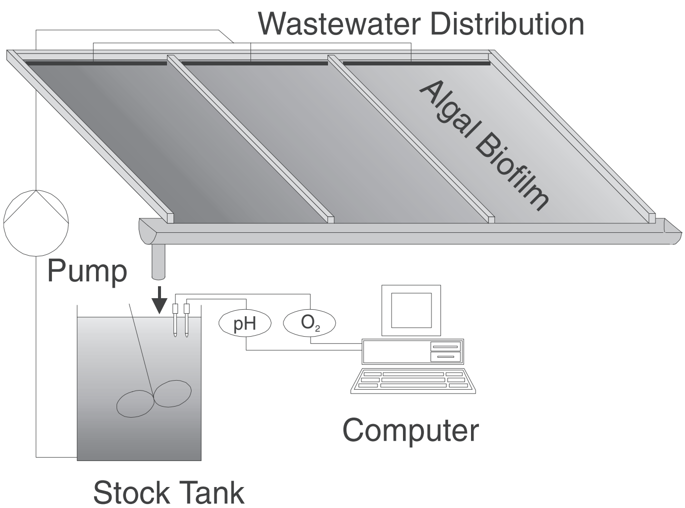

Figure 1 Algal biofilm experimental plant

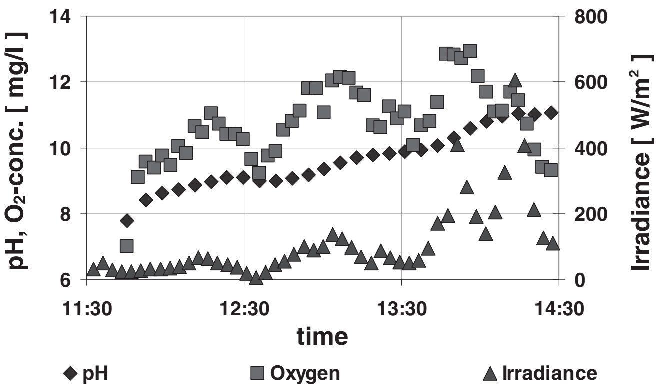

Figure 2 pH and oxygen concentration in context with the global irradiance from 11.08.1999 (time of the eclipse from 12:00–13:00)

was high at low CO_2-concentration (Butler, 1991). The photosynthesis process of algae implies that dissolved carbon dioxide was consumed and oxygen was produced. By gas exchange with the atmosphere, O_2 was transferred from the water phase to the atmosphere, while CO_2 was adsorbed into the water phase. With increasing irradiance the algal biofilm consumed more CO_2 (measured as an increase in pH) and produced more oxygen so that the O_2 concentration was raised.

Due to the growth of algae concentrations of total inorganic nitrogen ($c_{NH4\text{-}N}$, $c_{NO2\text{-}N}$ and $c_{NO3\text{-}N}$) and total phosphorus in the wastewater decreased. Figure 3 shows a typical course of nutrient reduction by an algal biofilm. The nitrogen concentration was reduced in an approximately linear line according to the nearly constant growth of the algae, whereas the phosphorus concentration fell in an exponential way to a concentration less then 1 mg/l and then remained unchanged.

The first exponential part of the phosphorus concentration curve can be described by first order kinetics. The rate constant k_i was modified by including the surface of the algal biofilm ($A_{Biofilm}$) and the volume of treated wastewater (V_R), so that a general constant k'_i independent of surface and treated volume was obtained. With such constants it is possible to compare different experimental set-ups of algal biofilms.

$$\frac{C_P}{C_{P0}} = \exp\left[-k_P \cdot t\right] - k_P \cdot t \quad \text{with} \quad k_P = k'_P \cdot \frac{A_{Biofilm}}{V_R} \tag{1}$$

The effect of the initial ammonium concentration on the modified rate constants for phosphorus removal is shown in Figure 4 for different experiments. With increasing NH_4-N concentration the modified constants decreased in an exponential curve. The rise of pH by photosynthesis was impeded due to the production of H^+-ions by nitrification (Schumacher *et al.*, 1999) and by the use of ammonium as nitrogen source for the photosynthesis process itself (Brezonik 1994).

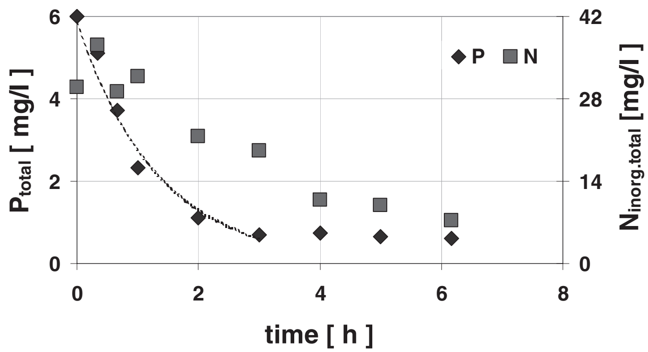

Figure 3 Typical course of phosphorus and total inorganic nitrogen removal

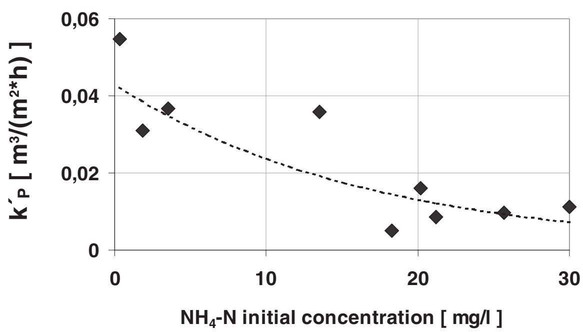

Figure 4 Effect on initial ammonium concentration on modified phosphorus reaction rate constants k'_P

The exponential fit of the modified rate constants was

$$k'_P = 0.043 \cdot \exp\left[-0.0596 \cdot c_{NH_4-N}\right] \qquad (2)$$

The dependence of phosphorus concentration on pH is shown in Figure 5. In the range of pH 6–7.5 no great influence of pH could be observed, the concentrations varied caused by small differences in initial P concentrations. In the pH range of 7.8–9.5 phosphorus concentrations decreased linearly to a concentration below 1 mg/l. At pH levels above 9.5, P concentrations were rather low and did not show a dependence on pH.

The concentration of dissolved carbon dioxide was reduced by photosynthesis and the pH consequently increased according to the reaction of the carbon dioxide equilibrium. Due to increasing pH hydrogen carbonate reacted to carbonate and precipitation of calcium carbonate occurred. In a simultaneous reaction, $H_2PO_4^-$ changed to HPO_4^{2-} by increasing pH. At pH 7.8 more than 80% of the phosphate ions were present in the HPO_4^{2-} form. These anions adsorbed at the active centres of the growing calcium carbonate crystals and formed calcium phosphate combinations (Hartley *et al.*, 1997). The reduction of phosphorus was not only caused by growth of algae; rather phosphorus was precipitated as calcium carbonate compound.

Additional to the nutrient removal, an increased bacteria reduction was observed. The bacteria concentrations decreased exponentially (Figure 6). The imperative value of the EU-Directive 76/160/EWG (2000 CFU/100 ml for *E. coli*, 10000 CFU/100 ml for total coliforms) was achieved for *E. coli* and total coliforms after 4 h. The reduction of faecal Streptococcus was almost negligible because of pollution of the biofilm by dove excrement from a nearby roof. Excrement of birds contains high amounts of faecal *Streptococcus* bacteria whereas the amount of coliform bacteria is far lower in general.

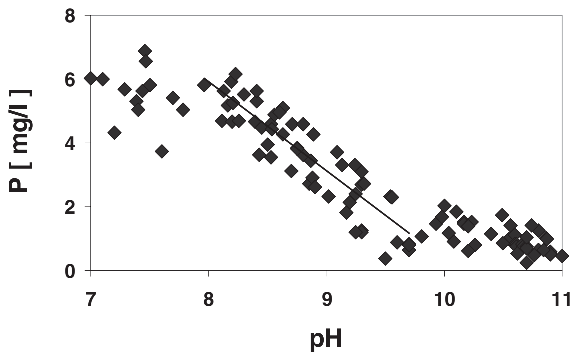

Figure 5 Dependence of phosphorus concentrations during solar irradiation of algal biofilm on pH

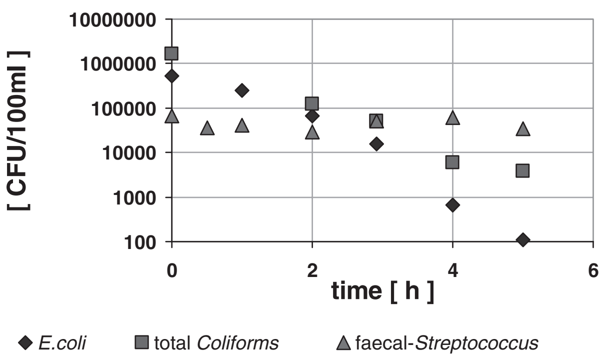

Figure 6 Typical course of bacteria reduction by an algal biofilm

Due to the exponential course the bacteria reduction can be described as a first order reaction. The reaction rate constant was modified taking into account the algal biofilm surface $A_{Biofilm}$ and the reaction volume V_R.

$$\frac{C_{Bi}}{C_{Bi,0}} = \exp[-k_{Bi} \cdot t] \ \ with \ \ k_P = k'_P \cdot \frac{A_{Biofilm}}{V_R} \tag{3}$$

In Figure 7 the dependence of the modified constants of bacteria reduction k'_{Bi} on the average pH during experimental course is shown. With increasing pH the modified constants increased exponentially.

The determined exponential approximations for the modified bacteria reduction rate constants are

$$k'_{B.E.coli} = 2 \times 10^{-6} \cdot \exp[-0.9009 \cdot pH] \text{ for } E.coli \tag{4}$$

$$k'_{B.Colif.} = 9 \times 10^{-5} \cdot \exp[-0.5337 \cdot pH] \text{ for total Coliform} \tag{5}$$

$$k'_{B.Strept.} = 5 \times 10^{-5} \cdot \exp[-0.5046 \cdot pH] \text{ for faecal } Streptococcus \tag{6}$$

With the determined constants for phosphorus removal and for bacteria reduction the maximum loading rate q_{LR} of an algae biofilm surface by the use of a first order reaction kinetic can be calculated. Eq. (7) shows the determination of a continuous flow reactor and a sequence batch reactor. For dimensioning it is necessary to choose a target value, which should be reached with the algal biofilm treatment.

$$\ln\frac{C_{i,target}}{C_{i,0}} = -k'_i \cdot \frac{A_{Biofilm}}{V_R} \cdot t = -k'_i \cdot q_{LR}^{-1} \qquad q_{LR} = \frac{k'_i}{\ln\frac{C_{i,0}}{C_{i,target}}} \tag{7}$$

Figure 8 shows the loading rates for *E. coli* reduction in dependence of the pH. The imperative value of the EU-Directive on Bathing Water Quality (2000 CFU/100 ml) is chosen as the target value. At pH 9.5 the maximal loading rate for *E. coli* reduction is 25 l/(m^2·h) at an initial *E. coli* concentration of 3,000 CFU/100 ml and 3 l/(m^2·h) at 100,000 CFU/100 ml. Bacteria concentrations in the effluent of wastewater treatment plants vary in a broad range, e.g. *E. coli* from 10^5–10^6 CFU/100 ml (Popp, 1991). Our own investigations in the effluent of very small wastewater treatment plants for 4–12 habitants showed lower values

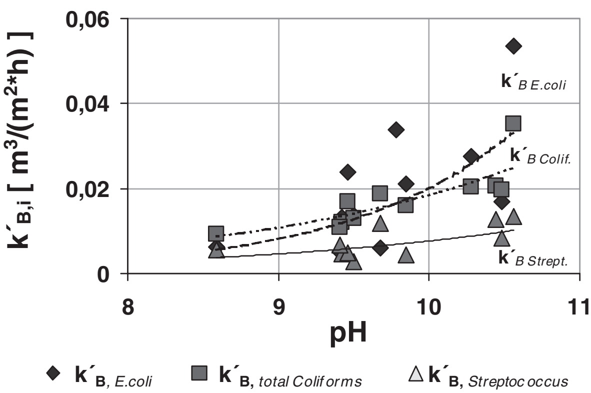

Figure 7 Dependence of modified bacteria reaction constants on average pH

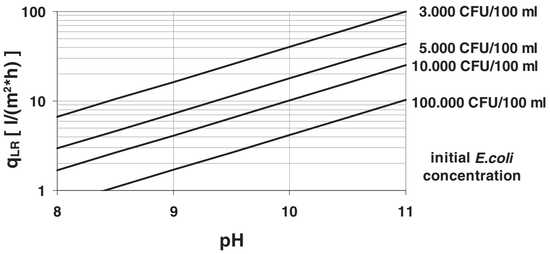

Figure 8 Maximal loading rates for the *E. coli* reduction for a target concentration of 2000 CFU/100 ml at different pH

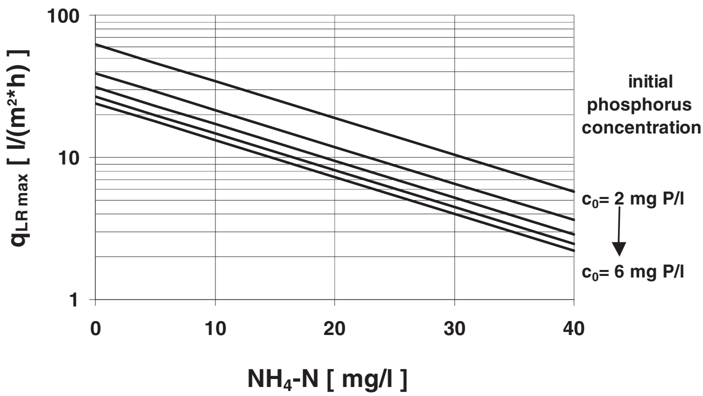

Figure 9 Maximal loading rates for phosphorus removal for a target concentration of 1 mg P/l dependent on the initial ammonium concentration

of 3,000–15,000 CFU/100 ml. Loading rates of 7 l/(m^2·h) and more can be achieved for small plants.

Due to varying bacteria concentrations in the effluent it is easier to dimension an algal biofilm process for phosphorus removal. Usual concentrations in treated wastewater were approximately 6 mg P/l and 15 mg NH_4-N/l. Figure 9 presents maximum loading rates for different initial ammonia concentration and a target concentration of 1 mg P/l. The maximum loading rate achieved a value of 10 l/(m^2·h).

Conclusion

The results of these investigations show the possibility of polishing the effluent of a wastewater treatment plant with the aid of an algal biofilm as a tertiary stage. Forming algae biomass reduced the nitrogen and the phosphorus concentration. Further the phosphorus was precipitated as calcium phosphate compounds with increasing pH. Additionally, a reduction of bacteria concentration occurred. High pH improves the reaction rate constant for bacteria reduction.

For dimensioning an algal biofilm system reaction rate constants for phosphorus removal and bacteria reduction were determined and an approach for estimating the required loading rates was presented. In an example, the loading rate for phosphorus removal was 10 l/(h·m^2). The achieved loading rates recommended an algal biofilm system as the tertiary stage especially for small wastewater treatment plants or wastewater ponds.

An algal biofilm process can be simply implemented and operated with solar energy. As a further effect, the water quality is improved by high oxygen concentration and nutrients from wastewater can be regained by harvested algal biomass.

References

Adey, W.H. and Loveland, K. (1998). *Dynamic Aquaria: Building Living Ecosystems*. Academic Press Inc.

Brezonik, P. (1994). *Chemical Kinetics and Process Dynamics in Aquatic Systems*. Lewis Publishers, Boca Raton, Florida.

Butler, J.N. (1991). *Carbon Dioxide Equilibria and Their Applications*. Lewis Publishers, Inc., Chelsea.

Canell Richard, J.P., Owsianka, A. and Walker, J. (1988). Results of a large screening programme to detect antibacterial activity from freshwater algae. *British Phycology Journal* (3), 41–44.

Craggs, R.J., Adey, W.H., Jenson, K.R., St. John, M.S., Green, F.B. and Oswald, W.J. (1996). Phosphorus removal from wastewater using an algal turf scrubber. *Water Science Technology*, **33**(7), 191–198.

Curtis, T.P. and Mara, S.A.S. (1992). The effect of sunlight on faecal coliforms in ponds: implications for research and design. *Water Science Technology*, **26**(7/8), 1729–1738.

Davies-Colley, R.J., Donnison, A.M., Speed, D.J., Ross, C.M. and Nagels, J.W. (1999). Inactivation of faecal indicator microorganism in waste stabilization ponds: interaction of environmental factors with sunlight. *Water Research*, **33**(5), 1220–1230.

Davis, L.S., Hoffmann, J.P. and Cook, P.W. (1990a). Seasonal succession of algal periphyton from a wastewater treatment facility. *Journal of Phycology*, **26**(4), 610–617.

Davis, L.S., Hoffmann, J.P. and Cook, P.W. (1990b). Production and nutrient accumulation by periphyton in a wastewater treatment facility. *Journal of Phycology*, **26**(4), 617–623.

Emeis, C.C. (1955). Über die Bedeutung der Algen bei der biologischen Reinigung des Oberflächenwassers. *Desinfektion und Gesundheitswesen* 153–159.

Epades Report: a4-0395 (1996). *http://www.europarl.eu.int/dg1/a4/de/a4-96/a4-0395.htm*

Hartley, A.M., House, W.A., Callow, M.E. and Leadbeater, B.S.C. (1997). Co-precipitation of Phosphate with calcite in the presence of photosynthesizing green algae. *Water Research*, **31**(9), 2261–2268.

Laliberté, G., Proulx, D., De Pauw, N. and De La Noüe, J. (1994). Algal Technology in Wastewater Treatment. *Advances in Limnology*, **42**, 283–302.

Pearson, H.W. (1987). Physio-Chemical Parameters Influencing Faecal Bacterial survival in waste stabilisation ponds. *Water Science Technology*, **19**(12), 145–152.

Popp, W. (1991). Desinfektion. Seminar: “Weitergehende Abwasserreinigung” am 19./20.Juni 1991. ATV und LGA Bayern, Nürnberg.

Pratt, R., Daniels, T.C. and Eiler, J.J. (1944). Chlorellin, an Anti-bacterial Substance from Chlorella. *Science*, **2574**(4), 351–352.

Schumacher, G., Ike, A., Patzold, V. and Sekoulov, I. (1999). Bacteria reduction of secondary effluent with an algal biofilm. *4th IAWQ Conference on Biofilm Systems*. 17.–20.10.1999. New York.

Sládecková, A. (1994). The role of periphyton in waste treatment technology. *Verh. Internat. Verein. Limnologie*, **25**, 1929–1932.

Uhlmann, D. (1988). *Hydrobiologie*. Gustav Fischer Verlag, Stuttgart.