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A COMPARATIVE STUDY OF SIX HYDROPONIC WASTEWATER TREATMENT PLANTS

En jämförande studie av sex hydroponiska avloppsreningsverk

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Abstract

During the last two decades, wastewater treatment in systems combining conventional biological processes and hydroponics has been tried at several locations. In this article, six different systems are described and their treatment results compared. Five systems were found in literature, and the sixth system was constructed and operated by the microbiology group at KTH. These systems can be divided into three subgroups: i) demonstration systems with small inflow and long hydraulic retention time (HRT), ii) pilot systems with small to moderate inflow and moderate HRT, iii) full scale systems with large inflow and short HRT. In general, removal of organic matter seems to be most efficient in systems resembling an active sludge process. Systems with long HRT appears over-dimensioned as long as the volume is not simultaneously used for treatment and production. Nitrogen was efficiently removed through conventional biological processes, whereas phosphorus removal through mainly sedimentation and adsorption in the systems was not very efficient. Nutrient removal by means of up-take through plant growth has not contributed significantly in any of the described treatment systems. None of the treatment plants have had the primary objective of biomass production. Hence, potential removal and recycling of nutrients through a productive system still remains to be answered.

Key words – wastewater treatment, hydroponics, BOD, nitrogen, phosphorus, greenhouse.

Sammanfattning

Avloppsvattenrening i system där konventionella biologiska metoder integreras med hydroponisk odling har använts på olika orter i drygt 20 år. I denna artikel beskrivs sex olika system, samt att deras uppnådda rening jämförs. Fem av systemen är tagna ifrån litteraturen, emedan det sjätte har byggts och drivits av Mikrobiologigruppen på KTH. Systemen kan delas in i tre grupper: i) demonstrationsanläggningar med små inflöden och lång uppehållstid, ii) pilotanläggningar med små till moderata inflöden och moderat upphållstid, iii) fullskalesystem med höga inflöden och kort uppehållstid. Generellt har rening av organiskt material varit mest effektivt i system som liknar en aktivt slam process. De system som har lång uppehållstid verkar överdimensionerade under förutsättning att volymen inte använts för både rening och produktion. Kväve har renats effektivt med konventionella biologiska metoder, emedan fosfor, som till stor del minskas genom sedimentation och adsorption i systemen, inte har blivit effektivt reducerat. Reduktion av näringsämnen genom upptag hos växande plantor har inte bidragit nämnvärt till den uppnådda reningen. Å andra sidan har inget av de inkluderade systemen haft produktion som primärt mål. Därmed återstår det fortfarande att utreda potentialen för rening och återcirkulering av näringsämnen i produktiva reningssystem.

Introduction

Wastewater treatment in systems combining conventional biological processes with hydroponic cultivation has been experienced at different locations during the last two decades. The use of macrophytes in wastewater treatment is theoretically beneficial for many reasons of which two proposed reasons are: i) recycling of nutrients through plant up-take, and ii) providing growth substrates for the microbial flora involved in the microbiological treatment processes (Reed et al., 1995). This article is partly based on a literature search performed during a doctoral study concerning hydroponic wastewater treatment under Swedish conditions. Five relevant

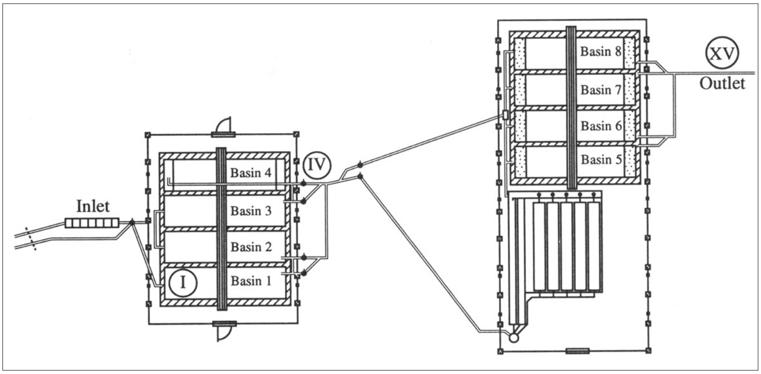

Figure 1. *Overview of the solar wastewater treatment plant at the Nordic Folkecenter* (Hinge and Hamish, 1997).

systems were found during the literature search. The sixth system, the Överjärva pilot plant, was constructed and investigated as part of the doctoral study. First the six systems are described briefly and then their documented potentials as treatment systems are compared and discussed. Included treatment parameters are organic matter, nitrogen and phosphorus.

Case studies

[1] Nordic Folkecenter for Renewable Energy, Hurup Thy, Denmark

This demonstration plant for treatment of domestic wastewater was started up in April 1989 at the Nordic Folkecenter for Renewable Energy, in Hurup Thy, Denmark. The main purpose of the project was to construct a model for decentralised treatment that involved little or no use of fossil energy. Secondly, focus was on reutilisation of the nutrient resources in the wastewater (Hinge and Hamish, 1997). The plant consisted of three independent parts covered with plastic greenhouses (Figure 1). The parts were a solar algae system (Basins 1–4), a ditch system and root-zone beds (Basins 5–8). Before the wastewater entered the first solar algae basin it passed an UV-filter for hygienic reasons. The central part in the plant was the solar algae system, which consisted of four basins in series, each 7x2 m and 1 m deep. Bacteria, algae, macrophytes as well as various kinds of invertebrates and fish inhabited the first three. In the last basin water was led through soil which was planted with *Typha* and *Iris*. The ditches were shallow hydroponics, 0.2 m deep, with macrophytes growing in the water, however, that part was mainly for experimental purposes and did not contribute significantly to the cleaning (Hinge and Hamish, 1997). The root-zone part consisted of four parallel basins of the same proportions as the solar algae system. The basins were filled with soil, and different kinds of plants were tested for their ability to transport oxygen into the soil (Hinge and Hamish, 1997). In 1991 the system treated 3–4 m^3 per day, and with a total wastewater capacity of approximately 100 m^3 the retention time was around 30 days (Boisen, 1995). Today, the system is still running and has been expanded (Kruse, personal communication). However, no further information has yet been published.

[2] Harwich, Massachusetts, United States – Solar Aquatics Systems©

This Solar Aquatic System™ (SAS) in Harwich, Massachusetts operated as a pilot facility for septage treatment from 1989 through 1992. Septage is concentrated waste generated by on-site wastewater treatment systems, and usually 50 to 100 times more concentrated than sewage (Peterson and Teal, 1996). These on-site systems consisted of a septic tank where solids settled by gravity and a leaching field where the liquid portion of the waste was treated and dispersed. They were used for rural or suburban houses and businesses, and the septage was usually collected from the tanks every 5 to 10 years. Septage was discharged from trucks through a bar screen/degritter tank into an in ground equalisation tank. Each truckload was highly variable and blending was an important part of maintaining a fully functional treatment system. Following equalisation the septage was conditioned by aeration and microbial additions before primary clarification. The microbial additions supplemented naturally occurring bacteria to speed reduction in BOD_5, fats, oils and greases. Following primary treatment the septage was gravity thickened in an unaerated tank. The solids were removed for further degradation in a separate part of the system, and the supernatant was pumped to the greenhouse portion where the remaining transport through the system was by gravity (Peterson and Teal, 1996). The major components of the pilot plant are shown in Figure 2.

The pilot facility was designed with aquaculture and constructed marsh components and located in a 465 m^2 greenhouse. The system ecology of the pilot facility was established in late March 1990 by filling the tanks and flooding the marsh with water from a nearby eutrophic pond (Peterson and Teal, 1996). The aquaculture subsystem consisted of three parallel rows of nine cylindrical, aerated, clear-sided tanks piped in series. The liquid depth in the tanks was 1.4 m and the surface area 1.65 m^2, thus providing a total surface area of 44.55 m^2. The hydraulic retention time (HRT) averaged 6.5 days for the aquaculture subsystem. A fine bubble aeration system ensured oxygen transfer and mixing adequate to maintain the solids in suspension. The tanks' surfaces were covered with floating plants, such as water hyacinth and willow, *Salix nigra*, which was supported at the sides of the tanks. Of the floating aquatic vegetation, water hyacinths usually looked the healthiest except in the winter months when their leaves died back from the cold. Air temperature in the greenhouse enclosure was controlled by thermostats set between 10–15°C, which was colder than the hyacinths preferred but more than adequate to maintain treatment quality (Peterson and Teal, 1996). A secondary clarifier followed the rows of tanks and the settled solids were recycled to the equalisation tank. A sand filter preceded the sub-surface flow marsh and protected it from clogging.

The constructed marsh subsystem was initially operated with three identical, parallel, 7.7 m long, small marshes made of lined, gravel-filled basins planted with reed canary grass, *Phalaris arundinacea*, and three-square bulrush, *Scirpus americanus.* There was a visible gradient of grass colour within the marsh, with the brightest green and densest stands at the waste-receiving end. The marshes were continually flooded to within 4–6 cm of the surface. The surface area of each marsh was 11.5 m^2 and the HRT was slightly under one day for the subsystem. For a portion of the time the facility operated, a marsh of double size with 1.7 days HRT was used. Maintenance of the biological system was generally self-sustaining, except for harvest from the tanks and marshes and intermittent carbon additions to the constructed marsh (Peterson and Teal, 1996).

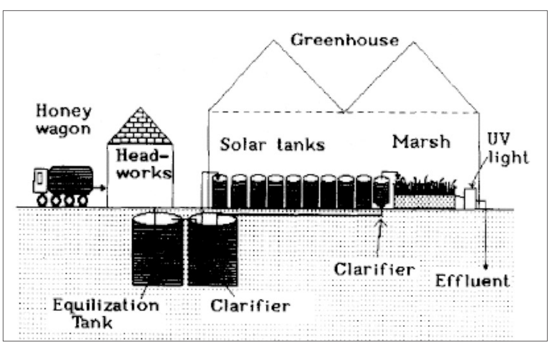

Figure 2. *Major components of the Harwich septage treatment pilot plant* (Peterson and Teal, 1996).

Table 1. *Nutrient removal pathways for the entire, including primary clarifier, Harwich septage treatment pilot facility for June 1991 through March 1992* (Peterson and Teal, 1996).

Average loading	Total-N 238 mg/L	Total-P 48 mg/L
Removal pathways:		
In sludge	62 %	65 %
In harvest	2 %	3 %
In effluent	4 %	13 %
As N_2	20–32 %	Balance unaccounted for

Of the nutrients supplied to the aquaculture, 4.4 % of the nitrogen and 2.5 % of the phosphorus were in the vegetation grown in the tanks. Vegetation was harvested as needed to prevent the plants from becoming too crowded or tall. In the marsh subsystem, 1.2 % of nitrogen and 0.3 % of phosphorus of the incoming nutrients were in the harvested biomass. The grasses and sedges in the marsh were cut off about 30 cm above the marsh surface and composted. Nutrient removal pathways are presented in Table 1. The phosphorus unaccounted for in Table 1 was likely bound to various substrates in the system (Peterson and Teal, 1996).

[3] Providence, Rhode Island, United States – Living Machines®

In Providence a 380 m^2 greenhouse structure hosted a Solar Aquatic™ living machine for sewage treatment that had been in operation since 1989. The designation Solar Aquatic was applied when tanks with translucent light transmitting sides were used for waste treatment. The first treatment room consisted of four rows of six tanks plumbed in series. The diameter of each tank was 1.83 m and the working volume was approximately 4.54 m^3. Water hyacinth provided the dominant surface cover. The first five tanks in each line were mixed and aerated with fine bubble diffusers. The sixth tank was without aeration and functioned to settle the solids (Figure 3). Solids were recycled to the first tanks in the series and periodically returned to the adjacent main sewage facility. The supernatant from these tanks flowed into a set of engineered tidal marshes in the second room. Each treatment line flowed into two gravel bed marsh trays, each around 2 m^2 and 0.5 m deep. These

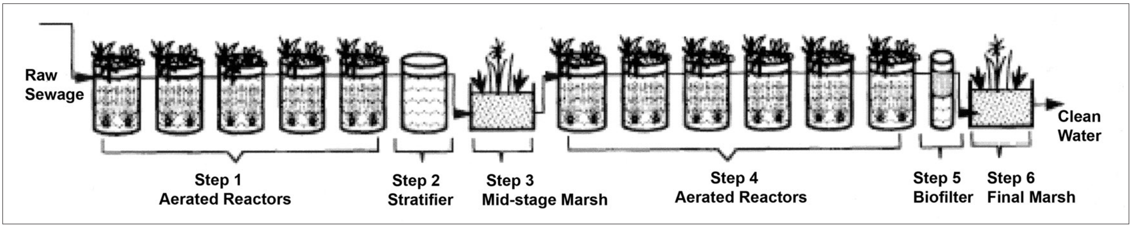

Figure 3. *Section through one single treatment line in Providence* (Todd and Josephson, 1996).

marshes were planted with wetland species, predominantly bulrushes, *Scirpus* spp. The flow was controlled to fill one marsh for 12 hours and then switched to the other marsh, which allowed the first to drain and dry. From the marshes the water was pumped back into another series of tanks. These tanks were stocked with a diverse community of racked and floating tropical and temperate plants. Animals included fish of the Cyprinidae family, snails, bivalve molluscs and zooplankton. A biofilter, filled with recycled plastic floating media, and a final marsh completed the treatment process (Todd and Josephson, 1996).

Measurements along a single treatment train showed that the bulk of reduction occurred in the first five cells, before the marsh. In addition, between 5–15 % of the metals, cadmium was an exception with 46 %, were found in the stabilised sludge which accumulated in the four Tank 6 Sludge clarifiers (Figure 4). Water hyacinths played only a minor role in metals uptake since no more than 1 % of the metals appeared in the plant tissue analysis (Table 2). The majority of the metals sequestered in the first six tanks was unaccounted for. Todd and Josephson (1996) suggested that the attached algal communities on the walls of the translucent tanks would be repository for the bulk of the metals, however, these communities were unfortunately not included in the analysis. Between September 1992 and August 1993, 27 m³ of sludge was removed from the four Tank 6 Sludge clarifiers (Todd and Josephson, 1996).

[4] South Burlington, Vermont, United States – Living Technologies, Inc.

This Advanced Ecologically Engineered System (AEES) was designed to treat 300 m³ per day of raw domestic wastewater to tertiary standards. The aim was to determine if the technology was capable of treating sewage to high standards, particularly during the cold and short day-length seasons. The system was started in late 1995, operated at its design flow capacity by May 1996 and was maintained at this steady state until the end of 1999 (Todd et al., 2003). The wastewater that entered the Vermont system was converted from the city's conventional treatment plant by a submersible pump located at the end of the degritting channel. Compared to the Providence system this plant had a slightly different setup, a new generation of Living Machines which hereafter was called AEES (Austin, 2000). The system had two equally configured treatment trains, A and B. Each train had five aerated reactors, 4.6 m wide and 4.6 m deep and a working volume of 57 m³, and the total HRT was 45 hours at the designed inflow. The reactors were originally all planted, however, plants were later removed from the first reactor to permit the installation of a compost biofilter on top of reactor 1A, and to install a fabric media tower in reactor 1B (Figure 5). Hence, the first reactors were converted from aerobic to anoxic reactors.

Effluent from the fifth reactor flowed to a 25 m³ clarifier. Biosolids from the clarifier were either sent to the

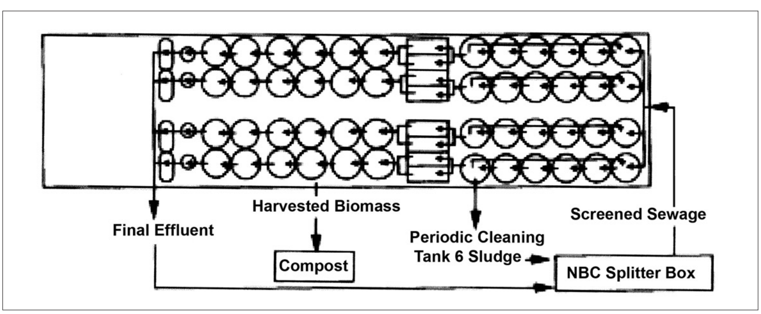

Figure 4. *Floor plan and diagram of the sewage treatment living machine in Providence* (Todd and Josephson, 1996).

Table 2. *Metal apportionment in the Providence LM®* (Todd and Josephson, 1996).

	Cd (%)	Cr (%)	Cu (%)	Pb (%)	Ni (%)	Ag (%)	Zn (%)
Sludge	42	8	7	15	5	12	8
Hyacinth uptake	1	1	0.1	1	0.2	0.2	0.2
Remainder in the first six tanks	56	91	98	85	95	88	91

first aerobic/anoxic reactor or to waste. The final tanks were three recirculating, downflow, vertical rock filters, which were called Ecological Fluidised Beds (EFB). These tanks were identical to the aerated tanks, however, the liquid volume of each filter was approximately 39 m^3. Initially, the filters had different functions. The first was aerobic and designed to nitrify clarifier effluent. The second was anoxic and designed to denitrify. In August 1996, methanol dosing started to provide a carbon substrate for the denitrification process. Dosing was discontinued by May 1999 for the B-train and July 1999 for the A-train. The third filter was designed for final effluent polishing of TSS. During the years several changes were made to the system, efficient nitrification and denitrification was achieved in the first five tanks and the filters were subsequently principally only used for TSS polishing (Austin, 2000). The total HRT of the system was 2.9 days (Todd et al., 2003)

The Austin report included an extensive study on green plants in wastewater treatment. Over 350 species of plants had been tested, and placed in categories A, B and C based upon a year-round performance evaluation by 13 criteria. The criteria included aspects such as; root mass development, low winter greenhouse temperature-tolerance, aesthetic appeal, potential economic value, level of required maintenance and general tolerance. Category A plant species were the top performers and thus recommended for further use, whereas Category C plants were failures and removed from the system. A list of 44 Category A vascular plant species was presented in the Austin report. The stated design role of the plants was to provide a large root mass surface area for attach-

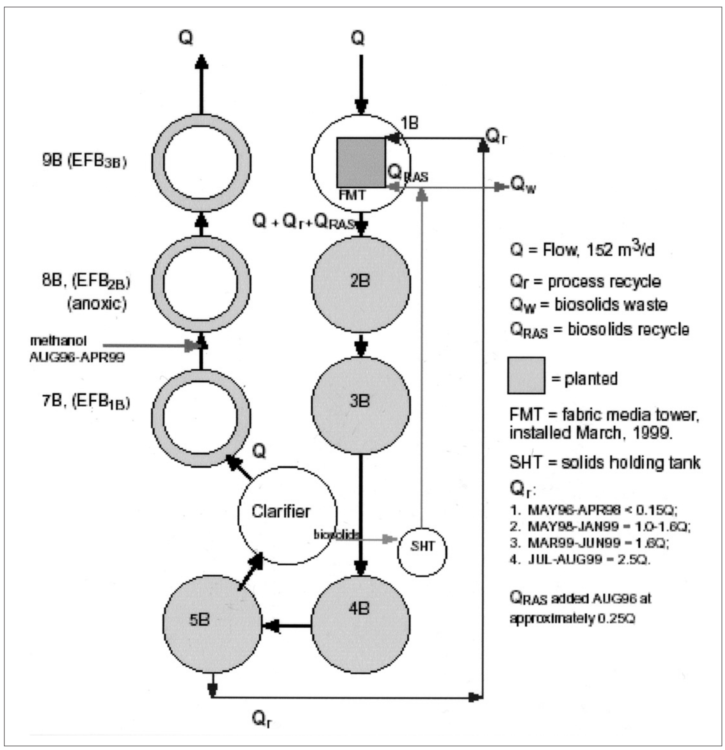

Figure 5. *Process schematic diagram for the Vermont B-train.* The A-train was a mirror image of this diagram except for reactor 1A (Austin, 2000).

ment of biofilms. However, the degree to which these biofilms contributed was not investigated. Further, no data on nutrient removal by means of up-take and subsequent removal of plants was included in the report. One interesting difference was reported from test train studies of planted and unplanted aerated reactors; the planted train appeared to have produced less biosolids. According to the operations logs, less than 20 gallons were wasted from the planted train over the period July 15 to August 12, 1999. During the same period, over 250 gallons of biosolids were wasted from the unplanted train. Unfortunately, evaluation of biosolids production was not part of the experimental protocol, hence no further quantitative information was available (Austin, 2000).

[5] Stensund wastewater aquaculture, Trosa, Sweden

The Stensund wastewater aquaculture, built in 1989, was a demonstration plant for indoor ecologically engineered wastewater treatment. Stensund Folk College, outside Trosa, Sweden (lat 60° N) was used as a model community of around 100 p.e. for the purpose of developing a recycling concept for the wastewater resources of nitrogen, phosphorus and heat energy (Guterstam, 1996). The steps through the Stensund wastewater aquaculture are shown in Figure 6. After primary settling, the wastewater was collected in a 28 m^3 concrete tank (1). An anaerobic 20 m^3 tank was used for degradation of organic compounds and precipitation of metal

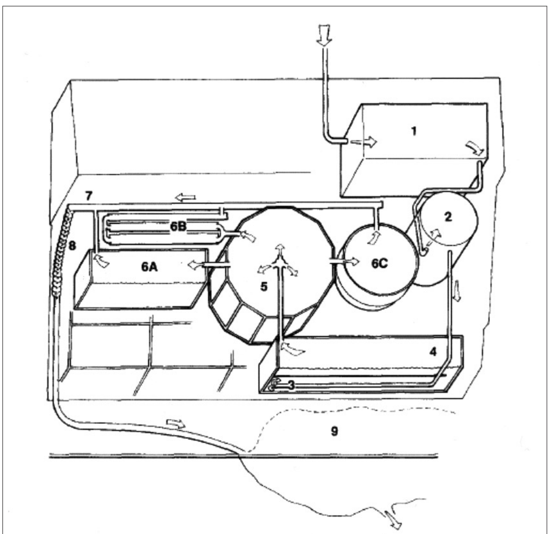

Figure 6. *Principal drawing of tanks and flows in the Stensund aquaculture system* (Guterstam, 1996).

sulphides by sulphur-metabolising bacteria (2). Steps 3 and 4 were in the same tank, they added up to a total volume of 27 m^3 and the entire water column was exposed to both artificial light and to sunlight. The bottom of the tank was built as a biofilter of pebbles with a vertical flow to continue the microbiological mineralization of the wastewater. The water volume of the aerobic bottom was 9 m^3 with a depth of 2–3 m (3). The rest of the tank was for phytoplankton cultivation (4). The next tank was 2.5 m deep, and the 40 m^3 volume was used for zooplankton cultivation while aquatic plants were cultivated on the 20 m^2 surface (5). Fish farming took place in (6a) and (6c), 12 m^2 surface area/27 m^3 volume and 9 m^2/9 m^3 respectively. The surfaces were covered with tropical aquatic plants (*Eichhornia crassipies*, *Pistia stratiotes*, *Hydrocleis nymphoides*), tropical ferns (*Azolla filiculoides*, *Salvinia auriculata*) and the temperate duckweed (*Lemna minor*). Two steps (6b) and (7) were used as hydroponics, 5 and 7 m^2 respectively, where vegetables and other plants like tomatoes and willows were grown. The last step inside the greenhouse was a water staircase of Flowforms (8), designed to aerate the water as it leaved the indoor part. The last part of the aquaculture was the outdoor crayfish pond (9). Finally, the water flowed down-slope to an energy-forest project planted with willows before entering the Baltic Sea (Guterstam, 1996).

After 4 years of operation (January 1990 – January 1994) the results showed that wastewater from 34 p.e. (0.18 m^3 $(d{*}p)^{-1}$) had been treated in the aquaculture. During this period, the average nutrient reduction in the aquaculture was 24 % for nitrogen and 17 % for phosphorus. Metals were reduced by anaerobic treatment, with 48–73 % reduction of seven identified metals (Guterstam, 1996). During a second evaluation period, January 1994 – September 1996, the reduction of organic material was similar to the previous period and the reduction occurred mainly in the early steps, from the inlet to the biofilter. The reduction for both nitrogen and phosphorus were approximately 30 %, however, the nutrient reduction could not be correlated with the production of plant biomass (Guterstam et al., 1998). The Stensund wastewater aquaculture was closed down in May 2000.

[6] Överjärva Gård, Solna, Sweden

At Överjärva Gård, close to Stockholm, Sweden, a small scale system was constructed to treat domestic wastewater. The intention was to treat the wastewater and at the same time use the nutrients for cultivation of valuable plants. The aim was to investigate the possibilities of using this kind of system in Sweden, and to compare it to conventional wastewater treatment systems from a

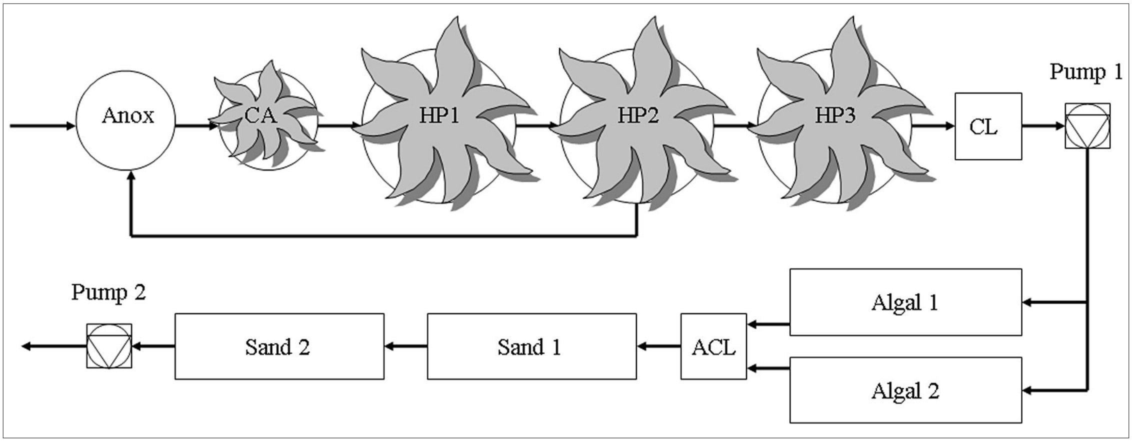

Figure 7. *A schematic overview of the Överjärva system in July 2002.*

sustainability point of view (Norström et al., 2003). The Överjärva system has been in operation since March 2001, and an overview of the system is presented in Figure 7. The treatment system was composed of several parts; anoxic tank (Anox), closed aerobic tank (CA), hydroponics (HP1–HP3), clarifier (CL), peristaltic pump (Pump 1), algal tanks (Algal 1–Algal 2), algal clarifier (ACL), sand filters (Sand 1–Sand 2) and effluent pump (Pump 2). The first tank was closed, and 60 % of the tank volume was filled with water and 300 L of Kaldnes carriers. The anoxic condition in the tank was used for denitrification of water recycled from the second hydroponic tank. In the first aerated tank (CA) aerobic degradation of organic material started. This tank was covered with a planted earth filter, and the air-filled volumes of the anoxic tank and the closed aerobic were connected. Thus, the earth filter cleaned released air and gases and successfully prevented odours in the greenhouse. In the next three tanks (HP1–HP3) aquatic and terrestrial higher plants were grown hydroponically (Figure 8). The hydroponics each held 1.57 m^3 of water and the surface area of 1.96 m^2 was available for plant growth. The water flowed by gravity to the sump of the peristaltic pump (Pump 1), which was used to obtain continuous flow in the algal tanks. The algal tanks were constantly aerated to keep the algae in suspension and to provide CO_2. From the algal tanks, each 1.2 m^2 and 0.2 m deep, the water flowed to the non-aerated sand filters. Sand occupied 50 % of the volume and the filters were planted with vascular plants. The inflow to the system was 0.56 m^3 per day, which resulted in a HRT of 12.7 days (Norström et al., 2003).

Figure 8. *The Överjärva system April 2003. To the left is the closed aerobic tank, which is followed by the hydroponic tanks* (Photo by Kaj Kauko).

Discussion

The systems included in the following discussion are: [1] Folkecenter, [2] Harwich, [3] Providence, [4] Burlington, [5] Stensund and [6] Överjärva. These six systems can be divided into three subgroups: i) demonstration systems with small inflow and long HRT [1, 5], ii) pilot systems with small to moderate inflow and moderate HRT [2, 3, 6], iii) full scale system with large inflow and

Table 3. *A summary of the involved treatment systems, including hydraulic conditions and influent and effluent concentrations for discussed treatment parameters.* * nitrogen concentrations reported as ammonia.

	inflow [m³/day]	HRT [days]	BOD [mg/L]		Total-N [mg N/L]		Total-P [mg P/L]	
			in	out	in	out	in	out
[1] Folkecenter[a]	3–4	30[b]	250	15[b]	80	8	13	1.5
[2] Harwich[c]		7.5	475	0	67	9.5	22	6
[3] Providence[d]	34	4.5	60–280	10	7–15*	1*	4	2
[4] Burlington[e]	300	2.8	207	4	31	5	6	2
[5] Stensund[f]	5–6[f,g]	24.5	110–130[g]	12[g]	47	28	6	4
[6] Överjärva[h]	0.6	12.7	286	29	94	23	15	7

a) Hinge and Hamish, 1997; b) Boisen, 1995; c) Peterson and Teal, 1996; d) Todd and Josephson, 1996; e) Austin, 2000; f) Guterstam, 1996; g) Guterstam et al., 1998; h) Norström et al., 2003.

short HRT [4]. The set-up and construction of the systems clearly shows a mutual basic idea of how treatment can be performed, although it is also possible to follow a development of techniques as experience has increased over the years.

The treated amounts of organic matter (BOD) and nutrients depended to a large degree upon the source of the inflow and the alternative for primary treatment. Flows were local domestic wastewater followed by primary settling [1, 5, 6], screened municipal sewage [2, 3] and supernatant originated from septage that had been collected in an equalizing tank followed by aeration, microbial addition and clarification [4]. Further, [1] had an UV-filter for hygienic treatment situated directly after the primary treatment, although it was not effective due to the high turbidity and high BOD content of the water (Boisen, 1995). A large part, about 40–60 %, of the nutrients was detained in the primary sludge [4, 5]. Thus, inflow values and achieved reduction presented in Table 3 are based on the actual concentrations in the influents after primary treatment. However, many numbers are means and approximations, and therefore the results are to be regarded as a general overview.

All the plants removed BOD and COD, and the reported BOD levels were, all but one, below the Swedish secondary treatment standards for BOD of 15 mg/L (Table 3). In the effluent of biological systems there will almost always be remaining BOD due to residual natural organic materials (Reed et al., 1995). However, Peterson and Teal (1996) contradictory reported that no BOD passed from the Harwich aquaculture to the marsh subsystem. The three systems with the shortest HRTs [2, 3, 4] showed the highest daily reduction of BOD (Figure 9). Considering that the depth of their aerated tanks were 1.4 m or more, and that [2] reportedly contained solids in suspension, the biological process responsible for removal of BOD in these systems probably resembled an activated sludge process. In [6] plant roots occupied a larger proportion of the tank volume and with no retained suspended solids, the active process was probable more like a biofilm associated with the roots. The last two demonstration systems [1, 5] appears to be over-dimensioned, at least regarding reduction of organic material. None of the treatment plants have been stressed to reach their treatment capacity neither by change in concentrations nor hydraulic residence time. However, maximum flow at [3] was limited by hydraulic constraints due to the existing inter-tank couplings (Todd and Josephson, 1996).

Ammonium reduction was good and apart from occasional problems, such as malfunctioning pumps, effluent levels of below 1 mg NH_4-N/L were constantly reached. However, Boisen (1995) reported troubles with nitrification during a second round of analyses at [1] and proposed that one possible reason could be the cold temperatures. In contrast, none of the other systems have reported seasonal decrease in treatment capacity. The Burlington project demonstrated two ways of running the denitrification process: methanol addition to the second EFB-filter in each train, and recycling of nitrified effluent and MLSS to a front-end anoxic reactor. The second method, using the carbon sources in the inflow, proved to be significantly more successful than the first (Austin, 2000). In total, this system had the highest removal rate for nitrogen (Figure 9). The Överjärva system also had internal recirculation with a subsequent high removal rate. However, due to high nitrogen concentrations in the influent the effluent did not reach the Swedish standard limit of 15 mg N/L with 200 % recir-

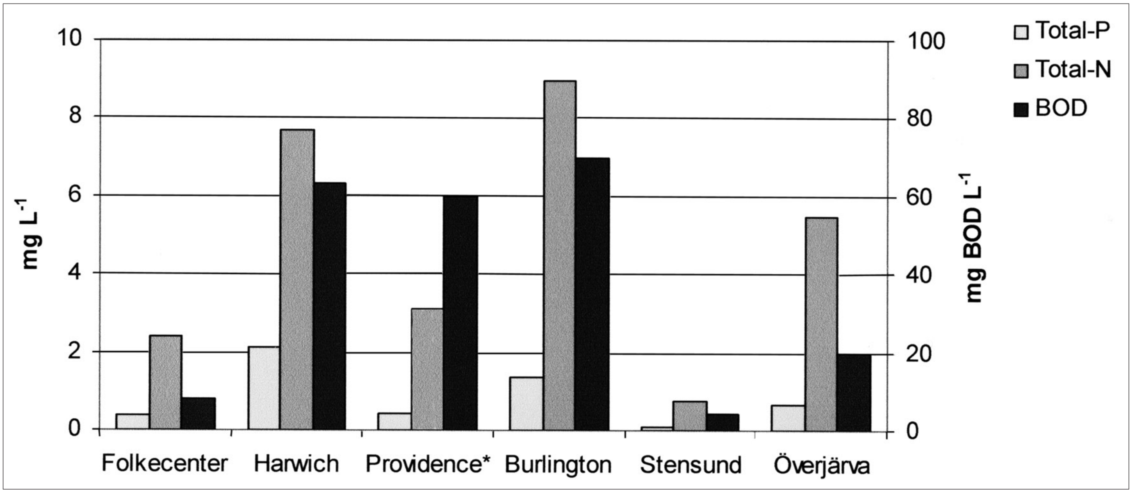

Figure 9. *Reduction per day in the different treatment plants. BOD values on the right y-axis.* * Nitrogen presented as ammonia concentrations.

culation (Table 3). Efficient denitrification was achieved in the Harwich marsh subsystem through regular additions of acetate. The external carbon source was added since the natural production of organic matter by decomposition of plants was insufficient (Peterson and Teal, 1996). In [3] only ammonia concentrations were reported, thus the actual nitrogen reduction is unknown.

Phosphorus reduction in the systems was not satisfactory compared to Swedish standard effluent levels of 0.5 mg P/L. Achieved reduction between 32–88 % resulted in effluent concentrations around 2–7 mg P/L (Table 3). The highest and lowest percentage reduction was reached in the two demonstration plants with long HRT [1, 5]. In general, most of the reduction was assumed to be due to sedimentation and adsorption in the systems. Therefore a high water volume/planted area quota, as in [5], seems to be unfavorable for phosphorus reduction. Peterson and Teal (1996) reported a 8 % reduction through up-take in removed macrophytes for [2] (3 % of the entire average loading). In [4] the majority of the reduction was achieved through removal of biosolids from the system, whereas in [6] the main reduction took part in the algal step and sand filters.

Conclusions

- Removal of organic matter appeared most efficient in systems resembling an activated sludge process.
- Systems with long HRT appeared over-dimensioned as long as the volume is not simultaneously used for treatment and production.
- Efficient nitrogen removal was achieved through conventional biological processes.
- Phosphorus was removed by sedimentation and adsorption in the systems, however, these processes were not very efficient.
- Removal of nutrients by means of up-take through plant growth has not contributed significantly in any of the described treatment systems.
- Potential removal through a productive system remains to be answered since none of the treatment plants have had the primary objective of biomass production.

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