

Process performance assessment of algae-based and duckweed-based wastewater treatment systems

O.R. Zimmo*, R.M. Al-Sa'ed*, N.P. van der Steen** and H.J. Gijzen**

*Birzeit University, Faculty of Engineering, Department of Civil Engineering, P.O. Box 14, Birzeit, West Bank, Palestine

**International Institute for Infrastructural, Hydraulic and Environmental Engineering (IHE), P.O. Box 3015, 2601 DA Delft, The Netherlands

Abstract A pilot plant experiment was carried out to assess differences in environmental conditions and treatment performance in two systems for wastewater treatment: algae-based ponds (ABP) and duckweed-based (*Lemna gibba*) ponds (DBP). Each system consisted of a sequence of 4 equal ponds in series and was fed with a constant flow rate of partially treated wastewater from Birzeit University. Physico-chemical parameters and the removal of organic matter, nutrients and faecal coliforms were monitored within each treatment system over a period of 12 months. The results show clear differences in the environmental conditions. In ABP significantly ($P > 0.05$) higher pH and DO values were observed than in DBP. DBP were more efficient in removal of organic matter (BOD and TSS) than ABP. The faecal coliform reduction was higher in ABP. However, the quality of the effluent from the third and fourth duckweed pond (total retention time of 21 and 28 days) did not exceed the WHO-criteria for unrestricted irrigation during both the summer and winter period, respectively. During the summer period, the average total nitrogen was reduced more in ABP (80%) than in DBP (55%). Lower values were measured during the winter period. Seasonal nitrogen reductions of the two systems were significantly different ($P > 0.05$). In DBP, 33% and 15% of the total nitrogen was recovered into plant biomass and removed from the system via duckweed harvesting during the summer and winter period, respectively. This study showed that there were differences in the environmental conditions and treatment efficiencies between the two systems.

Keywords Algae ponds; duckweed ponds; faecal coliform; *Lemna gibba*; treatment efficiency; wastewater

Introduction

Presently the application of conventional wastewater treatment systems in countries with low GNP is limited because of high cost and technological complexity. Worldwide, there is a continuous interest in algae-based waste stabilisation pond systems that are inexpensive and are known for their ability to achieve good removal of pathogens and organic pollutants. However, high algal concentrations of about 100 mg TSS/l may be occasionally reached in the effluent (Middlebrooks, 1995), causing severe clogging problems in advanced (drip) irrigation systems (Pearson *et al.*, 1995). These types of sustainable technologies for wastewater treatment, which are within the economical and technological capabilities of developing countries, need to be developed further. Introducing an aquatic plant (duckweed) to algae-based waste stabilisation ponds in order to increase nutrient recovery in a so called duckweed-based pond could be an appropriate alternative.

Duckweed-based pond (DBP) systems are low cost and do not need sophisticated equipment, high energy or qualified labour input. Contrary to algae-based ponds (ABP), DBP systems may generate biomass that is known to be an excellent source of feed for fish or poultry raising (Skillicorn *et al.*, 1993; Oron, 1994) and yields good effluent quality for irrigation. Improvement of effluent quality and recovery of nutrients will enhance the application of stabilisation pond systems and may offer important economic advantages for many developing countries. Different studies have shown that duckweed systems are capable of treating wastewater (Edwards, 1980; Reddy and DeBusk, 1985; Zirschky and Reed, 1988;

Alaerts *et al.*, 1996) and suspended solids in the effluent are reported to be much lower than for conventional ABP.

Most of the studies available in literature comparing the performance of DBP and ABP systems were carried out on ponds with different configurations, loading rates and location. Therefore, the aim of this study is to assess, under identical conditions, the seasonal differences in process performance of the two systems.

Materials and methods

Experimental setup of the pilot plant

This study was carried out using a pilot scale pond system at the new campus of Birzeit University (BZU), 26 km north of Jerusalem ($31^{\circ} 57' 32''\text{N}$, $35^{\circ} 10' 43.8''\text{E}$, 750 above m.s.l.). The pilot plant was built with reinforced concrete walls to ensure water tightness. It consists of a holding tank (2.2 m length, 1.3 m width and 1.9 m depth) followed by two parallel systems: algae-based ponds (ABP) and duckweed-based ponds (DBP). Each system consisted of a sequence of 4 equal ponds (3 m length, 1 m width and 0.9 m depth) in series (Figure 1). Baffles at the outlet of each pond were constructed to avoid short-circuiting and transfer of floating materials to the consecutive ponds.

Pond operation and monitoring

Approximately 0.9 m^3 of sewage from BZU was pumped daily to the holding tank from an aerated equalisation basin, which is part of the BZU activated sludge plant. The BZU treatment plant receives its sewage from the University new campus (3500 students) and septage ($60 \text{ m}^3/\text{week}$) brought by tankers from the student dormitory two times a week. The experimental pilot plant system has been operated from December 1998 onwards as a continuous flow system. A peristaltic pump pumped the wastewater from the holding tank at equal rates ($0.38 \text{ m}^3/\text{d}$ to each system) to the ABP and DBP. Duckweed-based ponds were started with *Lemna gibba* species at a density of $600 \text{ g fresh weight/m}^2$. Seasonal main characteristics of the influent wastewater to both pond systems are given in Table 1.

According to the classification by Metcalf and Eddy (1991) the wastewater is of weak to medium organic strength but contains medium to high nitrogen concentration. Wastewater composition is comparatively similar all year round. Further water transport to subsequent ponds in each train was by gravity. HRT of 7 days and water depth of 0.9 m is maintained in each pond. The final effluent of each system flows into a collection box and is channeled to the adjacent BZU activated sludge plant. A regular monitoring schedule was started 5 months after the pilot plant start-up. Grab samples (100-ml) were collected from the influent and the effluents of each pond once a week at 10:00 hours. For faecal coliform (FC) analyses, samples were collected using sterile 100 ml glass bottles. Dissolved oxygen (DO)

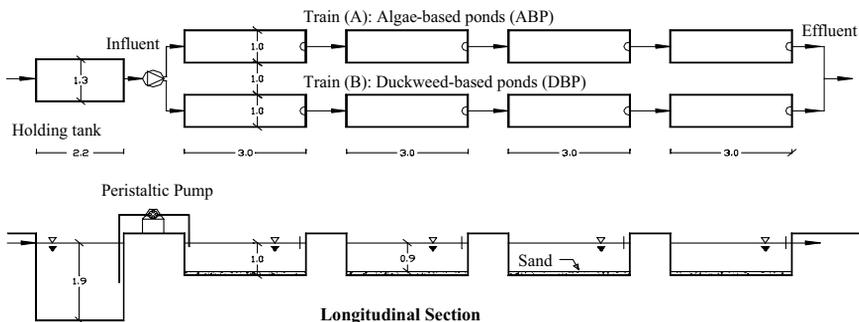


Figure 1 Schematic diagram of the pilot plant (all dimensions are in metres)

Table 1 Mean seasonal physico-chemical and microbiological characteristics of the influent to the ABP and DBP systems. Number of measurements were 17, 4, 16 and 12 during summer, autumn, winter and spring respectively. Data are presented as means (\pm standard deviation). All values are in mg/l unless otherwise stated

| Parameter | Summer | Autumn | Winter | Spring |
|-----------------------------------|-------------|-------------|-------------|-------------|
| Ambient T ($^{\circ}$ C) | 24 (3) | 19 (1) | 10 (3) | 23 (4) |
| pH ($-$) | 7.7 (0.2) | 7.5 (0.2) | 7.6 (0.2) | 7.7 (0.2) |
| DO | 0.8 (0.2) | 1.1 (0.1) | 0.4 (0.2) | 0.9 (0.2) |
| BOD ₅ (total) | 167 (3) | 160 (27) | 149 (20) | 162 (17) |
| COD (total) | 302 (56) | 300 (42) | 291 (38) | 300 (26) |
| TSS | 230 (66) | 149 (30) | 140 (24) | 141 (44) |
| Chlorophyll <i>a</i> (μ g/l) | 71 (37) | 42 (10) | 8 (7) | 10 (8) |
| Total-P | 4.3 (0.3) | 4.3 (0.1) | 4.3 (0.3) | 4.3 (0.3) |
| FC (CFU/100 ml) | 2.24 10^4 | 2.01 10^4 | 1.95 10^4 | 1.90 10^4 |
| NH ₄ ⁺ -N | 60 (6) | 61 (4) | 60 (6) | 60 (3) |
| NO ₃ ⁻ -N | 0.2 (0.2) | 0.4 (0.1) | 0.3 (0.2) | 0.2 (0.1) |
| Organic-N | 4 (4) | 3.5 (1) | 4 (3) | 2.5 (1) |

and pH were measured at 10 cm below the surface of the water column at 16:00 hours. DO and pH profiles over 24 hour periods were also established regularly.

Analytical methods

The analytical methods were as described previously (Zimmo *et al.*, 2000).

Duckweed sampling and processing

During summer, autumn and spring seasons (the warm seasons) when duckweed growth was good, duckweed biomass was harvested every fifth day and duckweed density was restored to 600 g fresh weight/m². This density was selected to prevent overcrowding and to maintain sufficient cover to minimize the development of algae in duckweed ponds. Nitrogen content in duckweed was determined by analysing triplicate samples of stored and dried (105 $^{\circ}$ C) harvested duckweed from each pond three times per month. Fresh duckweed production rates were calculated from the final (D_f) and initial (D_i) fresh duckweed density during the harvesting cycle (t). The following formula was used: duckweed production rate = $(D_f - D_i)/t$. Dry weight of duckweed was calculated by drying sub-samples of the harvested duckweed at 105 $^{\circ}$ C.

Results

Environmental conditions in the ponds

In the top 10–15 cm of the water column and during the afternoon, higher DO values were observed in ABP (over-saturation during warm seasons and 5–6.4 mg/l during winter) than in DBP (3.5–5.7 mg/l during warm seasons and 2.6–3.5 mg/l during winter). DO concentrations in both algae and duckweed ponds decreased rapidly with the distance from the water surface (Figure 2).

In all ponds of both systems, DO concentrations were approximately zero in the lower 30 cm of the water column. Differences observed in depths and between the two systems were significant ($p < 0.05$).

The pH was highest near the surface of the water column and slightly decreased with the distance from the water surface. Higher pH values were observed in ABP than DBP (Figure 3). In warm seasons, the pH values of the water columns were 8.8–9.1 and 8.0–8.2 in ABP and DBP, respectively. Lower values were observed in winter (8.2–8.5 in ABP and 7.6–7.9

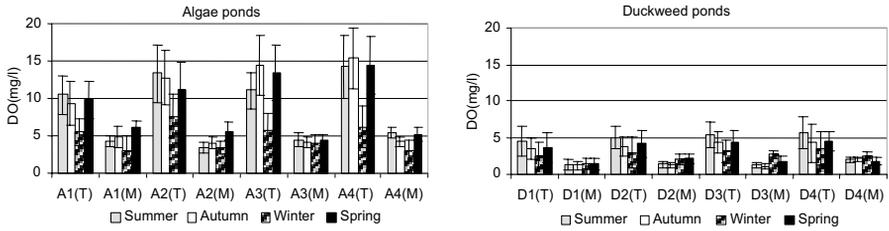


Figure 2 Seasonal means of DO concentrations at the top (T) and middle (M) depths during the afternoon in ABP and DBP. The error bars indicate the standard deviations

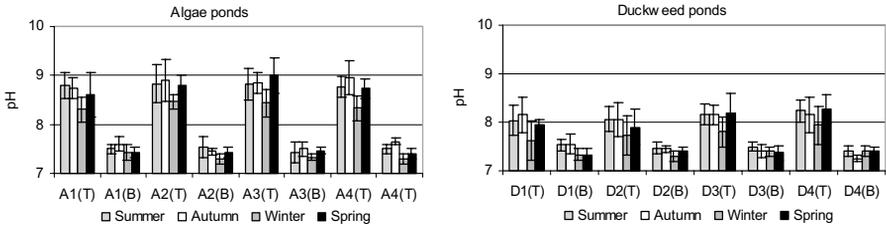


Figure 3 Seasonal means of pH values at the top (T) and bottom (B) depths in ABP and DBP. The error bars indicate the standard deviations

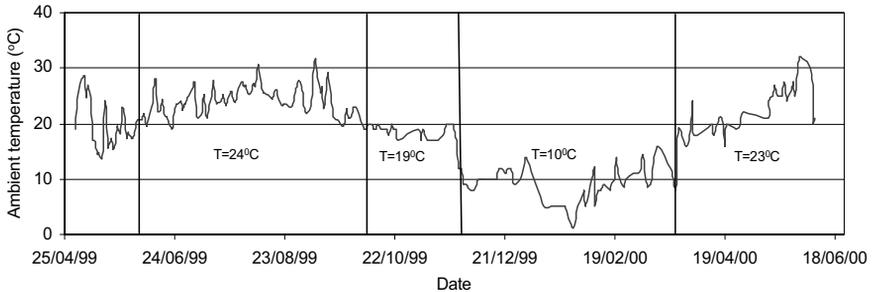


Figure 4 Average daily ambient temperature from the meteorological weather station at 600 m distance from the pilot plant

in DBP). In all ponds of the two systems, pH values in the sediment were approximately 7.5. Differences observed in depths and between the two systems were significant ($p < 0.05$).

Water temperature was highest at the surfaces than below in all ponds, however, differences with depth were not significant ($p > 0.05$). During warm seasons, shading caused by duckweed mat resulted in lowering the water temperature in DBP by approximately 1°C in comparison with water temperatures in ABP. During the afternoon, temperatures were highest in all ponds. Differences between water and ambient temperature were not significantly different ($p < 0.05$).

To determine the performance efficiency all year round as well as the effect of temperature, the average concentrations of different parameters from each pond of the two systems were calculated at four temperature ranges clustered as shown in Figure 4.

Organic removal

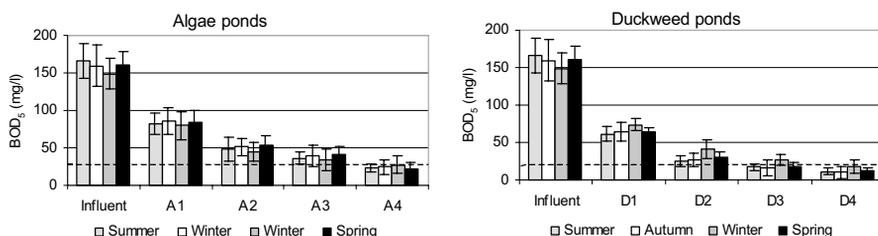
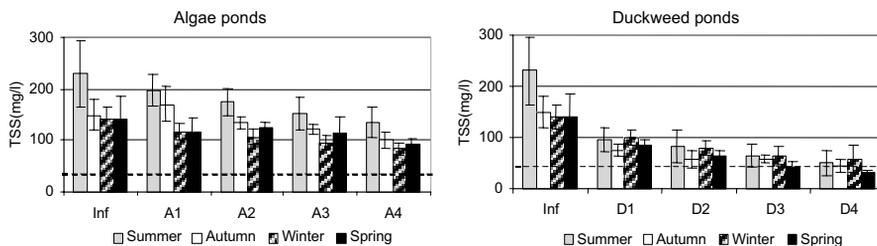
The effluent of the ABP contained higher concentrations of total BOD₅ (Figure 5) and TSS (Figure 6) than DBP. The influent organic load to each system during the year of monitoring ranged between 0.057 and 0.063 kg BOD₅/d.

Based on the daily organic load to the holding tank (0.2 kg BOD₅), each system will

Table 2 Mean seasonal values of FC (CFU/100 ml) of the influent and effluent of each pond in ABP and DBP systems

| | Summer | Autumn | Winter | Spring |
|----------|----------------------------|----------------------------|----------------------------|----------------------------|
| Influent | 2.24 10 ⁴ | 2.01 10 ⁴ | 1.95 10 ⁴ | 1.90 10 ⁴ |
| ABP | | | | |
| A1 | 3.72 10 ³ (0.7) | 2.95 10 ³ (0.8) | 6.83 10 ³ (0.3) | 3.07 10 ³ (0.7) |
| A2 | 3.50 10 ² (1.4) | 3.65 10 ² (1.0) | 1.98 10 ³ (0.4) | 4.53 10 ² (0.8) |
| A3 | 2.68 10 ¹ (1.7) | 3.00 10 ¹ (1.6) | 5.71 10 ² (0.4) | 4.30 10 ¹ (1.4) |
| A4 | 2.00 10 ⁰ (2.0) | 2.00 10 ⁰ (2.0) | 1.08 10 ² (0.6) | 3.00 10 ⁰ (1.8) |
| DBP | | | | |
| D1 | 5.58 10 ³ (0.4) | 7.75 10 ³ (0.2) | 9.74 10 ³ (0.1) | 6.24 10 ³ (0.2) |
| D2 | 1.82 10 ³ (0.3) | 2.97 10 ³ (0.2) | 6.11 10 ³ (0.1) | 2.10 10 ³ (0.2) |
| D3 | 5.36 10 ² (0.3) | 7.35 10 ² (0.4) | 3.17 10 ³ (0.1) | 5.43 10 ² (0.2) |
| D4 | 2.56 10 ² (0.2) | 2.05 10 ² (0.4) | 1.80 10 ³ (0.1) | 1.30 10 ² (0.2) |

Numbers in brackets represent the K_d values for first order removal day⁻¹

**Figure 5** Seasonal means of BOD₅ of influent and effluent of individual ponds. The error bars indicate the standard deviations. Dashed lines represent discharge standard**Figure 6** Seasonal means of TSS of influent and effluent of individual ponds. The error bars indicate the standard deviations. Dashed lines present discharge standard

serve approximately two population equivalents. During warm seasons, the organic loading rate (202–211 kg ha⁻¹ d⁻¹) to the first pond in both systems was approximately 50% lower than the maximum BOD₅ loading rate for facultative ponds using the modified linear approximation of McGarry and Pescod's equation adjusted by Arthur (1983). During the cold period, the loading rate (189 kg ha⁻¹ d⁻¹) was 26 % higher than the value calculated by the same model. In duckweed ponds, the annual average of the reductions in BOD₅ (92%) and TSS (71%) were higher than that in algae-based ponds (BOD₅: 85% and TSS: 37%). In both systems, no significant reduction in removal of BOD₅ and TSS were observed in the winter season. Chlorophyll *a* concentrations in ABP (270–2390 g/l) are approximately 6–15 times higher than concentrations in DBP (42–157 g/l). During the winter period chlorophyll *a* was less developed in ABP in comparison with warm seasons.

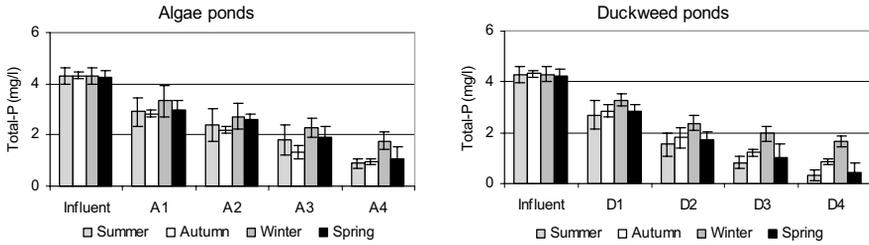


Figure 7 Seasonal means of total-P in ABP and DBP. The error bars indicate the standard deviations

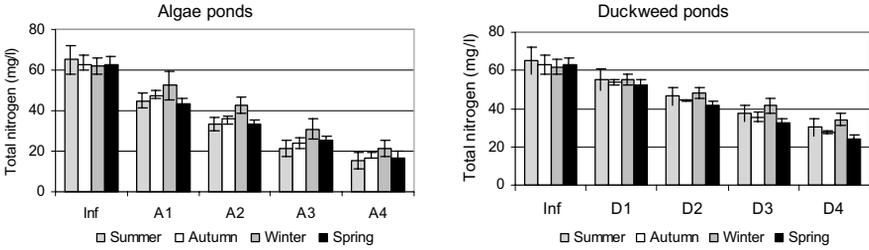


Figure 8 Seasonal means of total nitrogen in ABP and DBP. The error bars indicate the standard deviations

Faecal coliform removal

Although duckweed-based ponds were producing lower concentrations of BOD and TSS, they appeared less efficient for faecal coliform removal than the corresponding algae-based ponds. Seasonal faecal coliform (FC) counts performed on the influent and pond effluents in both systems are shown in Table 2. Removal of FC was respectively 3.3–3.6 and 1.3–1.7 log units in ABP and DBP during the warm seasons and 2.0 and 0.7 during the cold season.

The first-order rate constants (based on the assumption of completely mixed conditions) of faecal coliform die-off (K_b) were higher in ABP than in DBP and lower values in both systems were found during cold weather (Table 2). In algae-based ponds, K_b ranges were between 0.7–2.0 and 0.3–0.6 day⁻¹ during warm and cold seasons, respectively. In DBP, these values were 0.16–0.45 and 0.09–0.14 day⁻¹.

Nutrient removal

Phosphorus removal. The seasonal variations in total-P concentrations from each pond of the two systems are shown in Figure 7. Removal of total-P was respectively 74–79% and 74–92% in ABP and DBP during the warm seasons. Both systems had similar total-P removal efficiency (59% for ABP and 61 for DBP) during the winter season especially during the period when the duckweed cover disappeared due to low temperatures. Differences in the total-P reduction of the two systems were only significant ($p < 0.05$) during the summer and spring seasons.

Nitrogen removal. Despite the lower BOD and TSS removal efficiency in ABP, higher total nitrogen removal efficiency was achieved in comparison with DBP (Figure 8).

Removal of nitrogen in ABP was attributed to the nitrogen stored in the sediment, ammonia volatilisation and/or denitrification. In addition to the above mentioned removal processes, nitrogen recovery via duckweed harvesting is an important pathway for nitrogen removal in DBP. The highest nitrogen removal in ABP (77%) and DBP (62%) was achieved during the summer and spring seasons, respectively. For each individual pond of

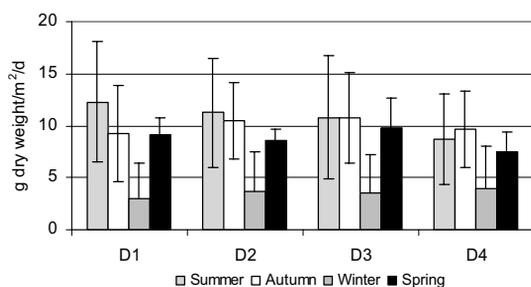


Figure 9 Seasonal means of duckweed growth rate in DBP. Error bars indicate standard deviation

the two systems, nitrogen removal in the first pond of both systems was highest. It was not surprising to measure lower nitrogen removal efficiency during the cold months (65% in ABP system and 45% in DBP system) as microbial, algal and duckweed activities and removal mechanisms are expected to be reduced. Nitrogen removal in the two systems was significantly different ($p < 0.05$) for all seasons.

Total nitrogen in the influent was mainly composed of ammonium ($\text{NH}_4^+\text{-N}$) and only a small fraction (5%) of organic nitrogen. Throughout the treatment systems, higher values of organic nitrogen were measured in effluents of ABP (5–10 mg/l during the warm seasons and 4–7 mg/l during the cold season) than DBP (1–3 mg/l all year round). Despite the fact that part of the nitrogen in ABP was incorporated in algal biomass as organic nitrogen and remained in the effluent, the overall nitrogen removal in ABP was higher than DBP. Annual total nitrogen removal in ABP and DBP systems was respectively 73% and 54% of the influent nitrogen after 28 days retention time.

Production of duckweed (Figure 9) in DBP varied from 7.5–12.3 and 3–4 g dry weight $\text{m}^{-2} \text{d}^{-1}$ during the warm and cold seasons respectively. Nitrogen content in duckweed was comparatively constant during various seasons. Average nitrogen content was 0.055 ± 0.01 g N/g dry weight. The contribution of duckweed to the N-recovery as duckweed protein via duckweed harvesting was 33% and 11% of total nitrogen input to the system during the warm and cold seasons respectively. The annual nitrogen recovery represented 23% of total nitrogen input to the system.

Discussion

Comparison of ABP and DBP systems revealed two obvious differences between the two systems. Firstly, ABP develop high densities of algae in the water phase, whereas algae are almost absent in DBP. Secondly, DBP maintain a dense cover of duckweed on the surface, preventing penetration of sunlight, whereas ABP do not have floating macrophytes on the water surface. The absence/presence of algae/duckweed resulted in differences in the environmental conditions in the two pond systems. The absence of algae in DBP led to a reduction of DO levels in the water during daytime. Oxygen production from the few algae present is low, while the dense cover of duckweed may have reduced oxygen diffusion from the air into the water phase. Duckweed may supply some oxygen to the water via transport of atmospheric oxygen through the root zone (Moorhead and Reddy, 1988), but this contribution is probably small as compared to the oxygen production by algae in ABP. In comparison with DBP, higher diurnal pH fluctuations were observed in ABP due to algal photosynthetic activities. The diurnal variation in DBP could be attributed to the photosynthetic activities by duckweed plants and/or algae that were present in low concentrations. The above differences in environmental conditions in the two systems are expected to affect both chemical and biological activities involved in the treatment processes in the ponds.

Lower total BOD₅ removal in the ABP system was found due to the presence of suspended algae in the effluent. Algae development and high TSS concentrations in ABP effluent will cause potential blockages of emitters if effluent is to be reused via drip irrigation. Also, the effluent standard for discharging into wadis in most countries in the world (20 mg/l for BOD₅ and 30 mg/l for TSS) could not be satisfied for the ABP system. In DBP, effluent standards for BOD₅ and TSS could be achieved after a HRT of 21 and 28 days respectively. Better removal of BOD₅ and TSS in DBP could be attributed to lower algal development and better sedimentation due to the effect of shading and quiescent conditions provided by duckweed cover. BOD₅ and TSS removal during the winter season were not reduced in both systems because of high HRT and lower organic loading rates especially in the last three ponds. BOD removal mechanisms in DBP are not fully understood. It has been suggested that *Lemnaceae* can take up simple amino acids and other organic compounds from the water (Hillman, 1961; Landolt, 1986), but Körner *et al.* (1998) concluded from laboratory studies with *Lemna gibba* that heterotrophic uptake of small organic compounds is not important. Nevertheless, they also found that COD removal was significantly faster in the presence of duckweed than in uncovered controls.

The results for BOD₅ and TSS removal in DBP were comparable to other studies using DBP for wastewater treatment. Alaerts *et al.* (1996) reported a BOD₅ removal of 95–99% in a full-scale treatment plant in Bangladesh at similar HRT of 20 days. Mandi (1994) reported BOD₅ removal efficiency of 60–70% in a pilot plant, which was operated with a cover of *Lemna gibba* at a HRT of about 7 days (equivalent to the effluent from the first duckweed pond in our system). These experiments were conducted with urban, domestic and industrial wastes with COD concentrations in the range of 305–530 mg COD/l and COD loading rate of 130–225 kg/ha.d. Similar removal of 80% of TSS has been reported in DBP systems (Mandi, 1994; Bonomo *et al.*, 1996; Zirschky and Reed, 1988).

Pathogen die-off results from complex interactions of several factors such as light radiation, depletion of nutrients, microbial antagonism, presence of antibacterial substances produced by algae, and high oxygen concentrations (Polprasert *et al.*, 1983; Pearson *et al.*, 1987; Saqqar and Pescod, 1992). Curtis *et al.* (1992a, b) suggested that FC removal in waste stabilisation ponds depends on synergistic interaction between pH, dissolved oxygen, humic substances and light. Our study showed that introduction of duckweed into the ponds affects these parameters. It seemed that direct sunlight, temporary and sharp fluctuations in pH contributed to higher pathogen removal in ABP than DBP. In ABP, using the model of Marais (1974) for determining the faecal coliform die-off coefficient K_b and using temperatures of 22°C and 10°C, which were the average ambient temperatures during warm and cold seasons respectively, K_b values of 3.7 and 0.5 d⁻¹ were obtained. The actual faecal coliform numbers in ABP effluent were in agreement with predicted values derived using the first order equation of faecal coliform reduction for determining effluent FC. FC levels as low as 2 CFU/100ml were detected in the effluent of the ABP system. Ponds three and four presented the highest value of K_b , however the effluent from the second (HRT=14 days) and third (HRT=21 days) algae ponds already satisfied the WHO guideline for unrestricted irrigation (1989) during the warm and cold seasons respectively. This was not surprising since the influent concentration (1.9×10^4 – 2.24×10^4 per 100 ml) was lower than that of typical domestic wastewater. The K_b values for the DBP were lower than for the ABP (Table 2). Environmental conditions in the DBP probably were not optimal for pathogen decay, due to reduced light penetration and algae growth. DBP systems, however, were able to satisfy the WHO guideline at higher HRT (21 days during the summer and more than 28 days during winter) in comparison with ABP systems.

The higher reduction of total-P in DBP could be attributed to duckweed uptake and subsequent removal by harvesting. Total-P removal in ABP was not effective due to the fact

that part of the phosphorus was taken up by algae and remained in the pond effluents. Also, upon the decay of algae biomass that has settled to the bottom of ABP, phosphorus would be released again into the water column.

Higher nitrogen removal was achieved in ABP than DBP. Removal via sedimentation during the summer period was presented elsewhere (Zimmo *et al.*, 2000). The remaining removal could be attributed to denitrification in the sediment layer and/or ammonia volatilisation. Nitrogen removal in ABP is comparable to that of Silva (1982) who obtained overall nitrogen removal of 81% in a system of similar depth (1.0 m) and hydraulic retention time (29 days). However, Middlebrooks *et al.* (1982) reported higher removal values in systems with very long hydraulic retention times of 227 days. In addition to denitrification and/or ammonia volatilisation in DBP, nitrogen recovery via duckweed harvesting (33% and 11% of total nitrogen input to the system during the warm and cold seasons respectively) presented an important removal mechanism. The nitrogen removal rate in the duckweed pond system was 1.2 and 0.9 g-N m⁻² d⁻¹ during the warm and cold seasons respectively. It was higher than values of 0.32 g-N m⁻² d⁻¹ reported by Alaerts *et al.* (1996) probably due to lower nitrogen concentration of the wastewater used in their system. Van der Steen *et al.* (1998) reported higher values for surface nitrogen removal (1.7 g-N m⁻² d⁻¹) in a shallow pond system that consisted of 7 duckweed ponds and 3 algal ponds. This can be explained by the more favourable surface-volume ratio of their ponds.

Availability of macro-nutrients (N and P) in the first three duckweed ponds was in excess (65–24 mg-N/l) and seemed not to be a limiting factor for duckweed growth. Although nitrogen concentration in the fourth duckweed pond was still in excess (34–24 mg-N/l), duckweed plants developed longer root length as compared to the first three ponds. This may be due to depletion of phosphorus and/or micro-nutrients in pond water. Low growth rates were observed for distinct periods during the 12 months monitoring: a period of infestation with aphids (Zimmo *et al.*, 2000), a period of heat stress due to very high ambient temperature and a period of cold stress during the winter period. During the first two periods, duckweed turned yellowish, got much smaller in size and lacked the gibbous morphology. During the winter period, duckweed growth was dramatically reduced and duckweed cover even disappeared for few days when the water temperature dropped below 5°C. Since such low temperature is not likely to occur for larger volumes of domestic wastewater, this will probably not be a problem in full scale wastewater treatment plants in the region.

Ammonium concentration in DBP varied between 60 mg/l in the influent to the first pond to 20 mg/l in the effluent from the fourth pond. The good growth of duckweed in all ponds suggests that ammonium concentration in this range did not affect the duckweed growth. Oron (1994) and Van der Steen *et al.*, (1998) reported comparable values for nitrogen uptake rates. Other authors however reported lower uptake rates (470 mg N m⁻² d⁻¹, Culley *et al.*, 1978; 420 mg N m⁻² d⁻¹, Corradi *et al.*, 1981; 500 mg N m⁻² d⁻¹, Tripathi *et al.*, 1991) probably due to differences in the experimental conditions. It is not possible based on this research to determine the importance of the other nitrogen removal processes (ammonia volatilisation and denitrification) in ABP and DBP systems. This will be the subject of further investigations. The wastewater used in this research is not representative for the region. Further work will be focussed to assess the relationship between the environmental conditions and system performance when operated with high strength wastewater.

Conclusions

Environmental characteristics and removal efficiency of organic matter, nutrients and faecal coliforms in algae-based and duckweed-based stabilisation pond systems were studied during a period of 12 months. The higher values in pH and dissolved oxygen in ABP were due to algal photosynthetic activities, which were suppressed in DBP as a result of shading

by the duckweed mat. The higher values in light penetration, pH and dissolved oxygen in algae ponds resulted in higher removal rates of faecal coliforms compared to duckweed ponds. In ABP, HRT of 14 and 21 days during warm and cold seasons were required to achieve faecal coliform reductions that comply with the WHO standard for unrestricted irrigation. In DBP, these guidelines could be fulfilled at longer retention time (21 days during the warm season and 28 days during the cold season). Higher BOD and TSS removal efficiencies were achieved in DBP compared to ABP. In both systems, the removal of BOD and TSS did not differ significantly during the different seasons of warm and cold weather. Total-P was more effectively reduced in the DBP system than in the ABP system, irrespective of the season. Higher total nitrogen removal efficiencies can be achieved in ABP than in DBP systems despite the fact that approximately one third of the influent nitrogen to the DBP is removed via duckweed harvesting. Lower removal efficiencies for nitrogen in both systems were obtained during the winter season. Nitrogen recovery via duckweed harvesting in DBP was reduced substantially during the winter season.

Acknowledgements

The authors are grateful to the Dutch government (SAIL) for financially supporting this research within the scope of the collaboration project between Birzeit University/West Bank and the International Institute for Infrastructural, Hydraulic and Environmental Engineering (IHE)/ The Netherlands. The authors would like to thank the laboratory staff members of the MSc. Program at Birzeit for their technical support.

References

- Alaerts, G.J., Mahbubar, M.R. and Kelderman, P. (1996). Performance of a full-scale duckweed-covered sewage lagoon. *Wat. Res.*, **30**, 843–852.
- Arthur, J.P. (1983). *Notes on the Design and Operation of Waste stabilisation Ponds in Warm Climates of Developing Countries*. World Bank Technical Paper No. 6, IBRD, Washington, DC.
- Bonomo, L., Pastorelli, G. and Zambon, N. (1996). Advantages and limitations of duckweed-based wastewater treatment systems. *5th International Conference on Wetland System for Water Pollution Control*, VIII/2, 1–8, Vienna.
- Corradi, M., Copelli, M. and Ghetti, P.F. (1981). Colture di lemna su scarichi zootechnical. *Inquinamento*, **23**, 49–45.
- Culley, D.D., Gholson, J.H., Chisholm, T.S., Standifer, L.C. and Epps, E.A. (1978). *Water Quality Renovation of Animal Waste Lagoons Utilizing Aquatic Plants*. US Environmental Protection Agency. Ada, Oklahoma. 166 pp.
- Curtis, T.P., Mara, D.D. and Silva, S.A. (1992a). The effects of sunlight on faecal coliforms in ponds: implications for research and design. *Wat. Sci. Tech.*, **26**(7–8), 1729–1738.
- Curtis, T.P., Mara, D.D. and Silva, S.A. (1992b). Influence of pH, oxygen and humic substances on ability of sunlight to damage faecal coliforms in waste stabilisation pond water. *Appl. Environ. Microb.*, **58**, 1335–1343.
- Edwards, P. (1980). *Food Potential of Aquatic Macrophytes*. ICLARM Studies and Reviews 5, 51 pp.
- Hillman, S. (1961). The *Lemnaceae*, or duckweed, a review of descriptive and experimental literature. *Botanical Reviews*, **27**, 221–287.
- Körner, S., Lyatuu, G.B. and Vermaat, J.E. (1998). The influence of *Lemna gibba* L. on the degradation of organic material in duckweed-covered domestic wastewater. *Wat. Res.*, **32**, 3092–3098.
- Landolt, E. (1986). *The family Lemnaceae – a Monographic Study*. Veröffentlichungen des Geobotanischen Institutes der ETH Zürich, Band 71: 566 pp.
- Mandi, L. (1994). Marrakesh wastewater purification experiment using vascular aquatic plants *Eichhornia crassipes* and *Lemna gibba*. *Wat. Sci. Tech.*, **29**(4), 283–287.
- Marais, G.v.R. (1974). Faecal bacterial kinetics in stabilisation ponds. *Journal of Environmental Engineering Division, American Society of Civil Engineers*, **100**, 119–139.
- Metcalf and Eddy (1991). *Wastewater engineering, Treatment, Disposal and Reuse*. G. Tchobanoglous and F.L. Burton (eds.). McGraw - Hill. New York.

- Middlebrooks, E.J., Middlebrooks, C.H., Reynolds, J.H., Watters, G.Z., Reed, S.C. and George, D.B. (1982). *Wastewater Stabilisation Lagoon Design, Performance and Upgrading*. Macmillan, NY, USA.
- Middlebrooks, E.J. (1995). Upgrading pond effluents: an overview. *Wat. Sci. Tech.*, **31**(12), 353–368.
- Moorhead, K.K. and Reddy, K.R. (1988). Oxygen transport through selected aquatic macrophytes. *Journal of Environmental Quality*, **17**, 138–142.
- Oron, G. (1994). Duckweed culture for wastewater renovation and biomass production. *Agricultural Water Management*, **26**, 27–40.
- Pearson, H.W., Mara, D.D., Mills, S.W. and Smallman, D.J. (1987). Physico-chemical parameters influencing faecal bacterial survival in waste stabilization ponds. *Wat. Sci. Tech.*, **19**(12), 145–152.
- Pearson, H.W., Mara, D.D. and Arridge, H.A. (1995). The influence of pond geometry and configuration on facultative and maturation waste stabilisation pond performance and efficiency. *Wat. Sci. Tech.*, **31**(12), 129–139.
- Polprasert, C., Dissanayake, M.G. and Thanh, N.C. (1983). Bacterial die-off kinetics in waste stabilization ponds. *Journal of Water Pollution Control Federation*, **55**, 285–296.
- Reddy, K.R. and DeBusk, W.F. (1985). Nutrient removal potential of selected aquatic macrophytes. *Journal of Environmental Quality*, **14**, 459–462.
- Saqqar, M.M. and Pescod, M.B. (1992). Modelling coliform reduction in wastewater stabilization ponds. *Wat. Sci. Tech.*, **26**(7–8), 1667–1677.
- Silva, S.A. (1982). *On the Treatment of Domestic Sewage in Waste Stabilisation Ponds in North East Brazil*. PhD thesis, University of Dundee, UK.
- Skillicorn, P., Spira, W. and Jouney, W. (1993). *Duckweed Aquaculture, a new Aquatic Farming System for Developing Countries*. The World Bank, Washington, USA.
- Tripathi, B.D., Srivastava, J. and Misra, K. (1991). Nitrogen and phosphorus removal capacity of four chosen aquatic macrophytes in tropical freshwater ponds. *Journal of Environmental Quality*, **18**, 143–147.
- Van der Steen, P., Brenner, A. and Oron, G. (1998). An integrated duckweed and algae pond system for nitrogen removal and renovation. *Wat. Sci. Tech.*, **38**(1), 335–343.
- WHO (1989). *Health Guidelines for the Use of Wastewater in Agriculture and Aquaculture*. Technical report series 778, 74 pp.
- Zimmo, O.R., Al-Sa'ed, R., van der Steen, P. and Gijzen, H.J. (2000). *Nitrogen Transformation and Treatment Efficiency in Algae-based and Duckweed-based Stabilisation Ponds*. Conference proceeding “Managing Water and Waste in the New Millennium”
- Zirschky, J. and Reed, S.C. (1988). The use of duckweed for wastewater treatment. *Journal of Water Pollution Control Federation*, **60**, 1253–1258.

