International Conference "Water, Environment, Energy and Society" (WEES–2009)
New Delhi, 12–16 January 2009

Lower Bounds for Removal of Pollutants from Sewage by Aquatic Plants

Y. Zimmels, F. Kirzhner[1] and A. Malkovskaja
Department of Civil and Environmental Engineering
Technion, Haifa - 32000, ISRAEL
E-mail: [1]kfelix@tx.technion.ac.il

ABSTRACT: Lower bounds for extraction of pollutants from sewage are investigated for the case of four floating aquatic macrophytes, water hyacinth (*Eichhornia crassipes*), water lettuce (*Pistia stratiotes*), salvinia (*Salvinia rotundifolia*) and water primroses (*Ludvigia palustris*). It is shown that lower bounds of biochemical oxygen demand (BOD), 1.3 mgL^{-1}, chemical oxygen demand (COD), 11.3 mgL^{-1}, total suspended solids (TSS), 0.5 mgL^{-1}, turbidity 0.7 NTU, ammonia 0.2 mgL^{-1}, and phosphorus 1.4 mgL^{-1} can be established for sewage purification with water hyacinth, and BOD, 1.8 mgL^{-1}, COD, 12.5 mgL^{-1}, TSS, 0.5 mgL^{-1}, turbidity, 0.9 NTU, ammonia, 0.2 mgL^{-1}, and phosphorus 1.6 mgL^{-1} with water lettuce. These lower bounds were reached in 11–17 days of experiments that were performed on diluted sewage with reduced initial contents of the tested water quality indicators. As expected, water hyacinth exhibited the highest rates and levels of pollutants removal, thereby producing the best lower bounds of the water quality indicators. Given their initially low levels, the BOD was further reduced by 86.3%, COD by 66.6%, ammonia by 97.8% and phosphorus by 65.0%, after 11 days of a batch experiment. The capacity of aquatic plants to purify dilute sewage streams opens new options for their application in the water treatment industry.

INTRODUCTION

The high productivity and pollutant removal capability of aquatic plants in wastewater treatment is well known (Reddy and DeBusk, 1985; Brix and Schierup, 1989; Kadlec and Knight, 1995). Natural aquatic systems have created substantial interest as regards their potential use for wastewater treatment and resource recovery, using green environments. These systems, which require low capital and offer competitive operating cost, are easy to operate and maintain.

Floating Aquatic Plants Systems (FAPS) have the following positive attributes: (1) high growth rate and productivity in the case of large-leaf floating plants; (2) high nutritional value relative to other emergent species; and (3) ease of harvesting and stocking (Boyd, 1974). Across the world, natural wetlands are populated by emergent vegetation (Droste, 1997).

In recent years plants such as water hyacinth (*Eichhornia crassipes*) and water lettuce (*Pistia stratiotes*) have been used for upgrading effluent quality (US Reddy and DeBusk, 1985; EPA, 1988; Tchobanoglous *et al.*, 1989; Kadlec and Knight, 1995).

In tropical countries water hyacinth is used because of its availability and high growth rate (Reddy and Sutton, 1984). The plants serve as a substrate for microbial activity that removes nutrients such as nitrates, ammonia and phosphates (Wolverton and McDonald, 1981; Bishop and Eighmy, 1989; Kumar and Garde, 1990). Among the floating aquatic plants, water hyacinth, generally considered to be a nuisance weed, has been extensively researched on laboratory, pilot and large scales, for nutrient removal from municipal wastewaters (Reedy and Smith, 1987). Most of the studies have focused on the treatment of wastewater. Relatively few studies have been reported on the use of floating plants for wastewater treatment with either high organic content (Whitehead *et al.*, 1987; de Casabianca-Chassany *et al.*, 1992; Polprasert *et al.*, 1992; DeBusk *et al.*, 1995, Costa *et al.*, 2000; Sooknah and Wilkie, 2004), or low initial load of pollutants. As of now, the effectiveness of plants in the dilute range of pollutants has not yet been determined. The question, how low can aquatic plants decrease the water quality indicators still remains open. Alternatively, it is of interest to determine lower bounds of pollutants content which can be reached due to their removal by aquatic plants, and under what conditions. This reflects on the range of application of aquatic plants for water purification.

In the purification process a complex variety of physical, chemical and biological processes is involved

---

[1] Conference speaker

in the transformation and consumption of organic matter and plant nutrients (Reddy, 1983, Reddy, 1984, Gersberg *et al.*, 1986, Reed *et al.*, 1988 and Jorgensen, 1994). It is well known that photosynthetically generated oxygen, by the water hyacinth, played an important role in the biodegradation of organic matter of the wastewater due to the action of aerobic and facultative bacteria (Polprasert and Khatiwada, 1998).

The use of free-floating water hyacinth is common place, because of its availability for wastewater treatment, high density surface coverage and high growth rate (Reddy and DeBusk, 1985; Reddy and DeBusk, 1987; Brix and Schierup, 1989; Tripathi *et al.*, 1990; Mishra *et al.*, 1991; Mitsch, 1994; Korner *et al.*, 1998, Polprasert and Khatiwada, 1998 and Saha and Jana, 2003). In tropical waters, as much as 0.08 g N/m^2 and 0.15 g P/m^2 per day can be removed by harvesting water hyacinth (Casabianca, 1985), at a mean production rate of 25 mg/m^2 per day of dry matter (DeBusk *et al.*, 1981).

The aquatic plants selected for this study included water hyacinth (*Eichhornia crassipes*), water lettuce (*Pistia stratiotes*) and water primroses (*Ludvigia palustris)*. Previous studies have shown that, among the floating macrophytes, these selected plants are expected to be more effective compared to small-leaf plants such as salvinia (*Salvinia rotundifolia*), azolla (*Azolla caroliniana*) and duckweed (*Lemna minor*) (Reddy *et al.*, 1983). However, water hyacinth and water lettuce are more sensitive to temperature (Clough *et al.*, 1987; Aoi and Hayashi, 1996).

In this study, the capacity of the aquatic plants to produce higher quality water from diluted sewage was investigated under laboratory conditions. This addressed the question of the highest purification levels which can be reached with aquatic plants. These purification levels are characterized by lower bounds of the water quality indicators. The lower these bounds are, the more effective are the plants, and the wider is their range of application. Furthermore, these lower bounds may depend on the initial load of pollutants, as expressed by the values of the water quality indicators at the start of the purification process. The lower bounds were compared with the levels of water quality indicators obtained with plants in fresh water, where, in the absence of other pollutants, the sole effect is that of the plants.

METHODS AND MATERIALS

Laboratory Experiments

Four sets of laboratory experiments were performed. The aquatic plants *Eichhornia crassipes, Pistia stratiotes, Salvinia* and *Ludvigia* were obtained from natural specimens grown in fresh water ponds in Israel. Sample collections and handling procedures were performed in the control and treated sewage, according to the proceedings recommended by Standard Methods (APHA, AWWA and WPFC, 1995). Samples were drawn by pipettes from the containers. Each BOD, COD, TSS and turbidity result is given as an average of two or three measurements taken from the same sample. The first, second and third sets of laboratory experiments were performed with 40 L identical containers (0.45 × 0.7 m^2 floor area). All tests were performed with aeration, and 30 min/h of continuous artificial light at 4600–4700 lux, 30–50% of daylight (produced by special lamps for plant growing, Figure 1), in each container during all experiments (24 h per day). Common practice with plants shows that they need light at 1000–5000 lux.

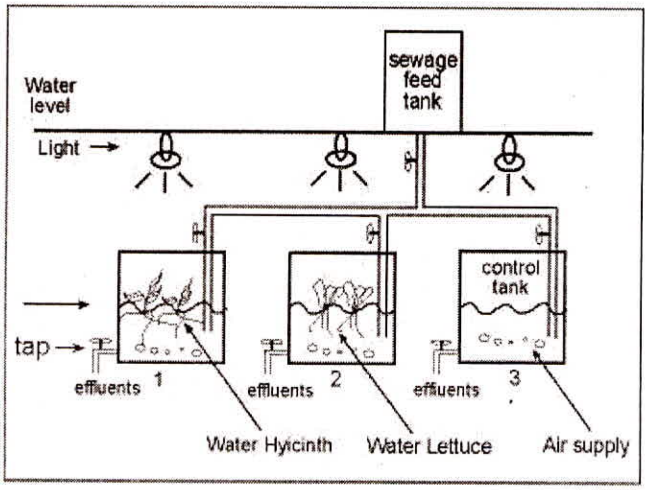


Fig. 1: Schematic layout of laboratory setup

The tests were carried out from 11 to17 days. After sewage addition to the fresh water, the COD level of the diluted water mixture was set at less than 30 mgL^{-1}. In sets 2 and 3 the same volume of sewage was added, every two or three days, to each container, keeping the total volume fixed (to this end, the same volume of water mixture was withdrawn from the containers prior to sewage addition).

Set No. 1. Three batch experiments were performed, the first and second with *Eichhornia crassipes* and *Salvinia*, while the third was used as control. Initially, at t = 0, the containers were filled with 26 L of fresh water and 1 L of pure sewage (see Figure 1). Aeration was applied at 0.3 Lmin^{-1}, 8–10 hday^{-1}. This set up provided the diluted sewage medium with the required lower initial values of the water quality indicators.

Set No. 2. Three batch experiments were performed, the first and second with *Eichhornia crassipes* and *Pistia stratiotes*, while the third was used as control. Initially, at $t = 0$, the containers were filled with 29 L of fresh water and 1 L of pure sewage. Aeration was applied at 0.3 Lmin^{-1}, 2–3 hday^{-1}.

Set No. 3. Three batch experiments were performed, the first and second with *Ludvigia* and *Salvinia*, while the third was used as control. At the start of the experiment, the containers were filled with 39 L of fresh water and 1 L of pure sewage. Aeration was applied at 0.3 Lmin^{-1}, 2–3 hday^{-1}.

Set No. 4. Three batch experiments were performed, the first and second with *Eichhornia crassipes* and *Pistia stratiotes*, and the third was used as control. Initially, at $t = 0$, the containers were filled with 30 L of fresh water. After 2 days, 5 L of water were withdrawn from each container, and 5 L of pure sewage were added (per container), so as to set the mixture volume back to the operating level of 30 L in all containers. The tests were performed in each container with 0.2 Lmin^{-1} aeration applied at 8–10 hday^{-1}.

Set No. 5. Five batch experiments were performed: the first, second and third with *Eichhornia crassipes, Pistia stratiotes* and *Salvinia;* the fourth and fifth with *Eichhornia crassipes* and *Pistia stratiotes*. Initially, at $t = 0$, the containers were filled with 6 L of fresh water. The tests were performed in each container without aeration, and no sewage was added. The first sampling was performed immediately after planting of the macrophytes. Table 1 summarizes the type of plants, water composition, and aeration conditions, in these experiments.

Outdoors Experimental Setup

The experimental setup, which was constructed in the yard of the Civil and Environmental Engineering department, was used to test performance of floating and emergent plants under different feed conditions of sewage and fresh water. To this end, use was made of a three floor section of the pilot pools. The pilot (total 121 m^2 floor area) consist of three sections: greenhouse with aquatic plants—14 m^2; free water surface system with aquatic plants (water hyacinth -*Eichhornia crassipes* and pennywort-*Hydrocotyle umbellate*)—62 m^2 floor area; constructed wetland with emergent plants (papyrus-*Cyperus Papyrus* cattails-*Typha Latifolia* and reed-*Phragmites Australis*)—45 m^2 floor area. The depth of pools was 0.6 m. In this test, two sections with floating and emergent plants were used. This pilot unit facilitates performance of simultaneous experiments with wastewater recirculation by pump. Experiments were performed as follows:

Initially, fresh water was used to support the plants, followed by dosage of sewage and mixing. Sewage was added in cycles, 2–2.2 m^3 /day, during the 55 day experimental period.

Table 1: Details of Experiments in Containers under Laboratory Conditions

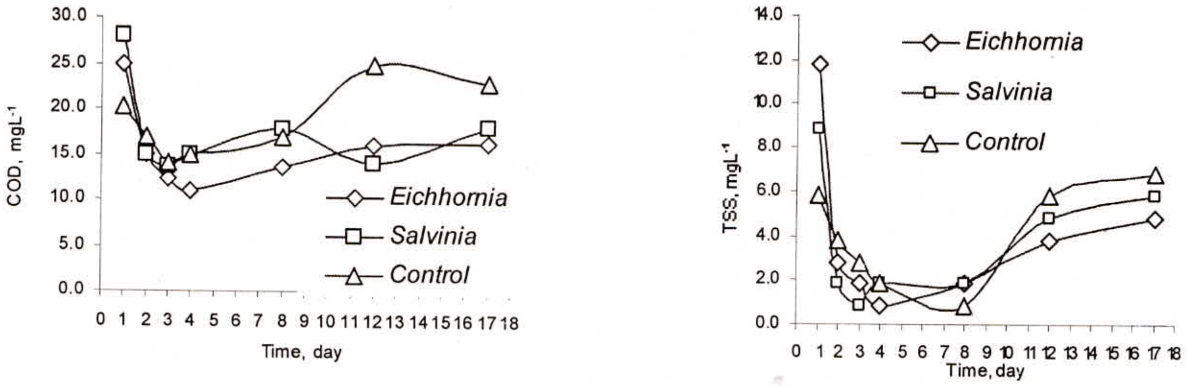
Set Number	*Test Number*	*Type of Plants**	*Water Composition**, L*	*Aeration Rate, Lmin^{-1}*
1.	1	EC	FW – 26, S – 1	0.3 (8–10 hday^{-1})
	2	SR	"	"
	3	Control	"	"
2.	1	EC	FW – 29, S – 1	0.3 (2–3 hday^{-1})
	2	PS	"	"
	3	Control	"	"
3.	1	LP	FW – 39, S – 1	0.3 (2–3 hday^{-1})
	2	SR	"	"
	3	Control	"	"
4.	1	EC	FW – 30, S – 5	0.2 (8–10 hday^{-1})
	2	PS	"	"
	3	Control	"	"
5.	1	EC	FW – 6	No aeration
	2	PS	"	"
	3	SR	"	"
	4	EC	"	"
	5	PS	"	"

*EC – Eichhornia crassipes; SR – Salvinia rotundifolia; LP – Ludvigia palustris; PS – Pistia stratiotes;

**FW – fresh water; S – sewage; for example FW - 26, S – 1 means fresh water – 26L, sewage – 1L. " – same.

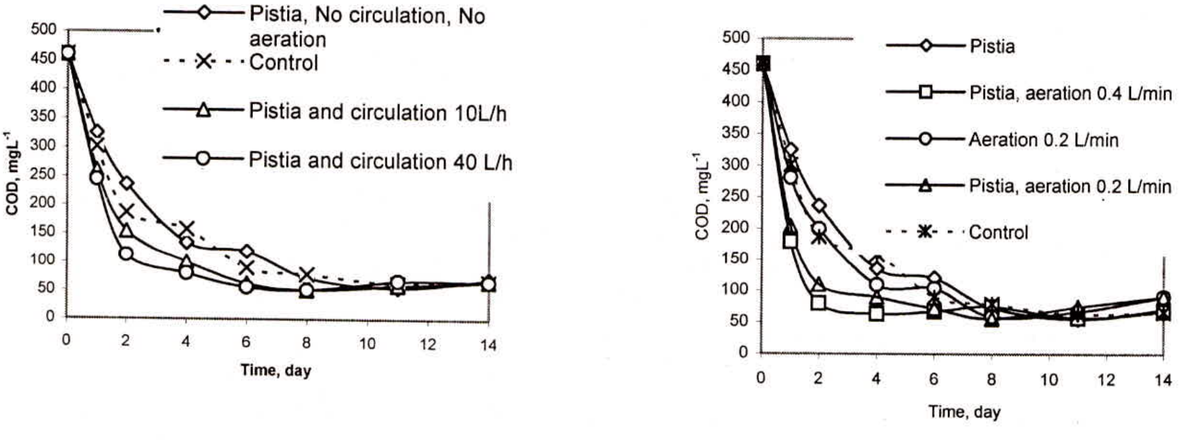
RESULTS

Set No. 1. Figure 2 depicts results of (a) COD and (b) TSS vs. time. Figure 2 shows that the plants *Eichhornia crassipes* and *Salvinia* are capable of decreasing the COD from 25 and 28 mgL^{-1} down to 11 and 13 mgL^{-1} (56.0 and 53.6% removal) after 3–4 days, respectively. The rate of change of COD with time, which is highest in day 1, decreases in day 2 until to vanishes in day 3 and 4 in the presence of *Salvinia* and *Eichhornia crassipes*, respectively. The plants are significantly more efficient as compared to the control, as regards the fraction of removed COD and the lowest COD level reached. Following the first minimum in all curves, a rise in the COD was observed. In the control, the rise in day 12 and 13 even exceeded the initial COD value. An important consequence of Figure 2 is that 3–4 days of treatment time is optimal, and further treatment produces less favorable results. Residual COD levels of 10–15 mgL^{-1} are remarkable when compared to the 50–70 mgL^{-1} obtained in many other tests. For example, Figure 3a depicts typical results for COD vs. time, obtained with initially higher level of this water quality indicator. After 8 days in the presence of *Pistia* plants, the COD removal (from its 460.5 mgL^{-1} initial value) with circulation set at 40 Lh^{-1} (best result), is estimated at 42.9 mgL^{-1}, as compared to 72.9 mgL^{-1} without circulation, and 78.8 mgL^{-1} in the control (with no plants and circulation). After 14 days with plants, and circulation tested at 10 Lh^{-1}, 20 Lh$^{-1,}$ 30 Lh^{-1}, and 40 Lh^{-1}, the COD increased to 53.7 mgL^{-1} (best result), the corresponding result without circulation being 70.3 mgL^{-1}, as compared to 66.5 mgL^{-1} in the control. Note, that here no further decrease of COD below 42.9 mgL^{-1} was possible. Similar behavior was observed in the presence of *Pistia* plants and aeration (Figure 3b). After 8 days in the presence of *Pistia* plants and 0.2 Lmin^{-1} aeration, the COD decreased (from its 460.5 mgL^{-1} initial value)



(a) (b)

Fig. 2: Results of test in the presence of *Eichhornia crassipes* and *Salvinia*: (a) COD vs. time; (b) TSS vs. time



(a) (b)

Fig. 3: COD vs. time in the presence of *Pistia*: a. effect of circulation; b. effect of aeration

down to 55.7 mgL^{-1} (best result), as compared to 72.9 mgL^{-1} without aeration, and 78.8 mgL^{-1} in the control (with no plants and aeration). Beyond the 8 day period, the COD level was slightly increased, in all tests. Results obtained using high, 460.5 mgL^{-1}, initial COD value in sewage showed that it could not be reduced below 50 mg/L (Figure 3). The combination of concentrated influent and the limited capacity of aquatic plants to handle high COD loads provides explanation for this fact.

Other water quality indicators behaved similar to the COD when their lower bounds were tested. In day 4, the TSS level dropped in the presence of *Eichhornia* plants, from its initially low level of 11.8 mgL^{-1} to 0.8 mgL^{-1}, (93.2% removal) but increased up to 4.8 mgL^{-1} thereafter, see Figure 2b. With *Salvinia* plants, the TSS level dropped from 8.8 mgL^{-1} in day 1 to 0.8 mgL^{-1} in day 3 (90.9% removal). In the control, the same level was reach, from the intial 6.0 mgL^{-1} (86.8% removal), only on day 8. Clearly, in day 1, the plants exhibit faster kinetics compared to the control, e.g., 10 mgL^{-1} day^{-1}, 7 mgL^{-1} day^{-1} and 2 $mgL^{-1}day^{-1}$ in the case of *Eichhornia*, *Salvinia* and the control, respectively. The turbidity level showed similar features (data not shown). The *Eichhornia* and *Salvinia* plants decreased the turbidity level from its initially low level of 5.8 down to 1.0 NTU (82.8% removal) in day 2. The lowest level of 0.69 NTU was observed in day 8 and 17 in the presence of *Eichhornia* plants. The plants were more efficient compared to the control regarding the kinetics of the turbidity removal, as well as, the capacity to prevent its rise with time. The water plants seem to buffer changes in the pH and keep its level stable between 7.16 and 7.62 (data not shown). For example, after 17 days, the pH of the mixture rose from 7.16 to 7.42 in the presence of *Eichhornia* plants, and from 7.16 to 7.62 with *Salvinia* plants. In contrast, a rise in the pH from 7.2 to 8.4 was observed in the control.

Note that the decrease in water quality indicators persisted for at least 3 days. Following a minimum an increase in these indicators was observed. This observation applies also to the control. The reason for the increase in the COD, TSS and turbidity levels after 3–4 days is not clear and can be due to changes in the water due to the activity and death of microorganisms that develop on the plants roots. The results of this set of experiments indicate that for diluted sewage, 4 days or less may be sufficient to achieve optimum results, whereas longer periods have adverse effects.

Set No. 2. Results of 5 cycles of sewage addition, in 1 L equal doses, each followed by a monotonic decrease in the COD are shown in Figure 4. The five 1 L doses of sewage were administered on day 2, 5, 7, 10 and 13. This appears on the time axis of the plot as two identical numbers, the first denoting the level reached by the COD,and the second the rise in COD due to the dose of sewage.

Each dosage, with no exception, produced an increase in the COD levels. In all cycles (except for the first one where the initial COD level was too low) the removal of pollutants with plants was greater compared to the control, and the gap thus formed increased with each additional dosage. After 15 days the COD level, in the presence of *Pistia* and *Eichhornia* plants, increased from 9.2 to 33.2 mgL^{-1}, as compared to 59.6 mgL^{-1} (Figure 4) in their absence. In general, the plants were capable to decrease the COD level by half or more, in all cycles. In contrast, less then a quarter was removed by the control. Thus the capacity of the plants to cut the COD levels further, even when their initial values are low, is established.

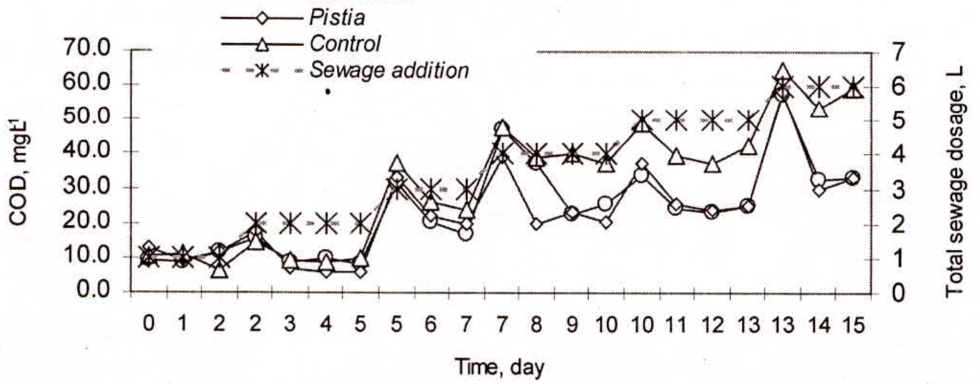


Fig. 4: Results of test in the presence of *Eichhornia crassipes* and *Pistia stratiotes*: COD and total sewage dosage vs. time

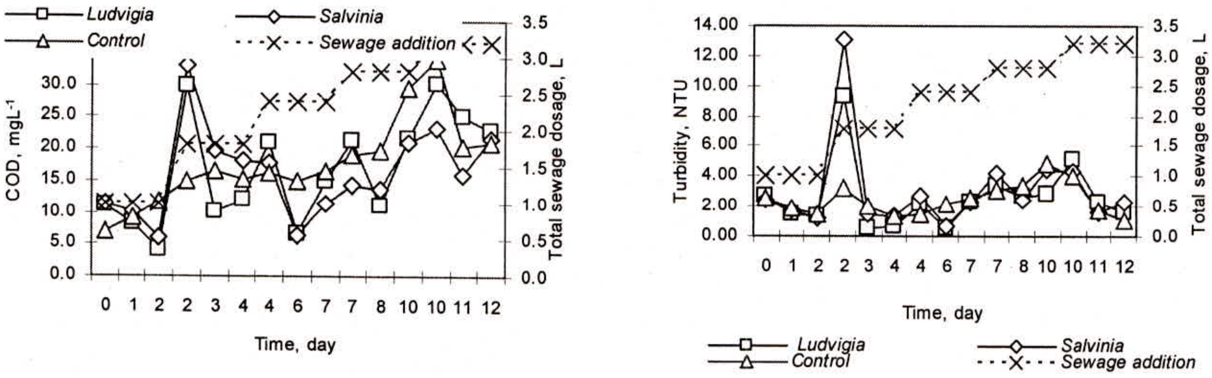
Set No. 3. The results of 4 cycles of sewage addition, in 0.5–1 L doses, each followed by an increase in the COD and turbidity are shown in Figure 5a and b, respectively. The dosages of sewage were administered on day 2, 4, 7 and 10. As expected, each dosage produced a local increase in the COD and turbitity levels. The rise in COD and turbidity reflected the dosage level (Figure 5a). For example, following the largest 1 L dose, in day 2, the steepest COD rise was observed, as expected. Except for day 6, 11 and 12, the COD increased with time in the control. In contrast, the plants were capable of decreasing the COD to 10 mgL^{-1} (day 3), 6 mgL^{-1} (day 6) and 10 mgL^{-1} (day 8), with removal efficiencies of 1/3 to 2/3 of the COD level generated by the last dose. This proves the capacity of the plants to purify water in these low COD levels. The performance of the *Ludvigia* and *Salvinia* plants is comparable in terms of kinetic and the COD levels.

The turbidity level showed a trend similar to that of the COD with monotonic decrease and increase from cycle to cycle, except for the first dosage where steeper turbidity rise and drop was recorded (Figure 5b). Superior performance of the plants was observed in day 3, 4, 6, 8 and 10 with values as low as 0.5 NTU, compared to 1.0 NTU in the control in day 3, 4 and 6. In contrast to the fluctuating nature of the curves in the presence of plants, the control produces monotonic increase in day 4 to 10.

Set No. 4. Figure 6 depicts results of (a) BOD, (b) COD, (c) TSS, (d) turbidity, (e) ammonia, and (f) phosphorus, vs. time in the presence of *Eichhornia* and *Pistia*. The initial water characteristics were as follows: BOD 9.5–10.2 mgL^{-1}, COD 31.8 –36.5 mgL^{-1}, TSS 14.5–16.5 mgL^{-1}, ammonia 9.5–10.2 mgL^{-1}, phosphorus 3.8–4.0 mgL^{-1}, and turbidity 5.9–6.2 NTU. These initially low values were set purposely to test the performance of plants in this range. After a treatment period of 11 days with *Eichhornia crassipes,* 89.6% of the turbidity, 86.3% of the BOD, 66.6% of the COD, 96.8% of the TSS, 97.8% of the ammonia and 65% of the phosphorus were eliminated. High removal of the BOD and COD were observed already in day 4 (Figurs 6a and b). Table 2 summarizes the results in day 11 as compared to day 1.

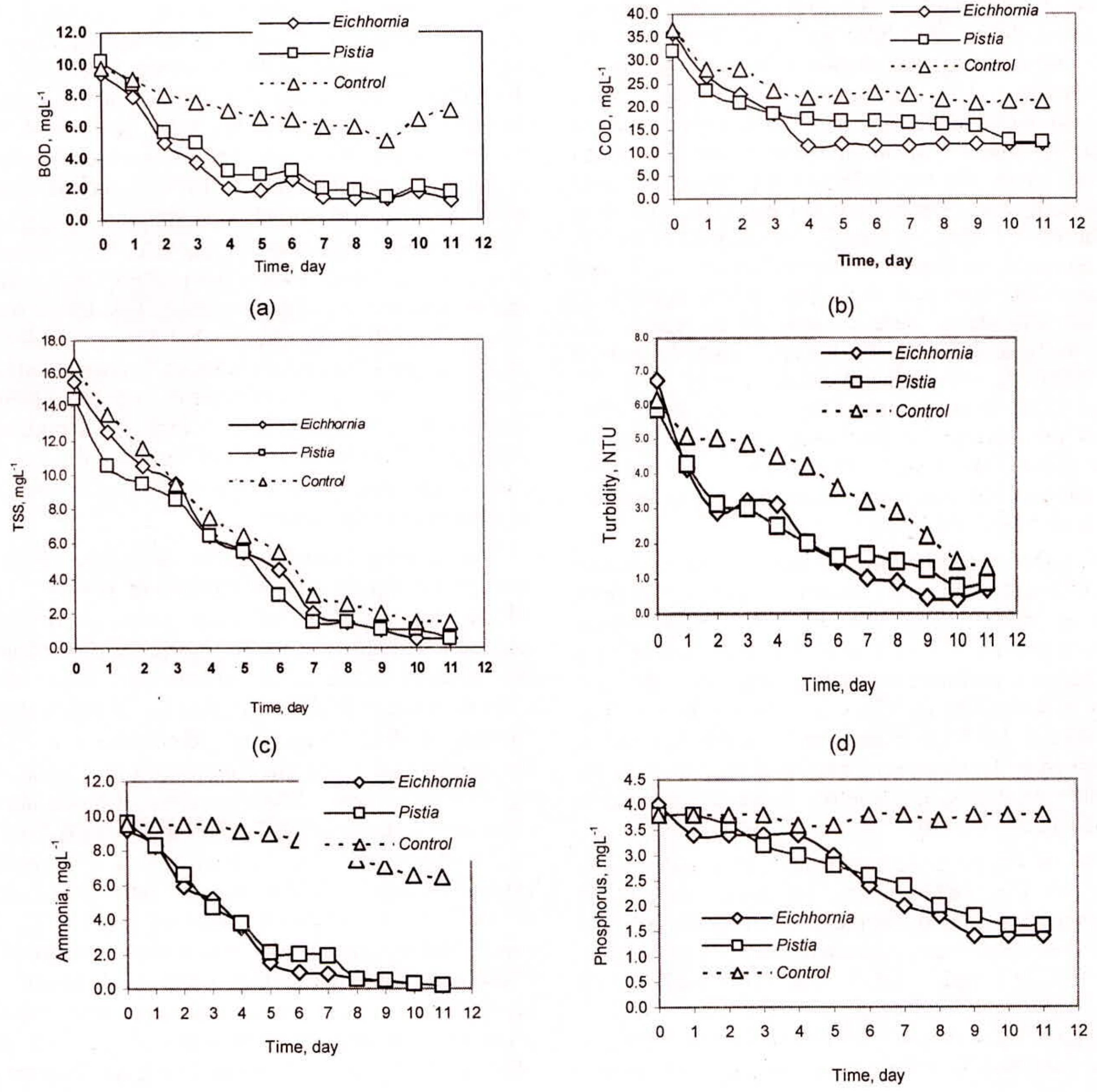
A treatment period of 11 days in the presence of plants reduced significantly the BOD, COD, ammonia and phosphorus from their initially low levels further down to the following levels: 1.3–1.8 mgL^{-1}, 11.9 –12.5 mgL^{-1}, 0.2 mgL^{-1} and 1.4 –1.6 mgL^{-1}, respectively (see Table 1), whereas in the control the corresponding changes were: 7.0 mgL^{-1}, 21.1 mgL^{-1}, 6.4 mgL^{-1} and 3.8 mgL^{-1}. Results of TSS and turbidity did not vary significantly due to the presence of aquatic plants e.g., as compared to the control.

The superior kinetic features of aquatic plants for sewage purification are illustrated in Figure 7 (a–c) which depicts plots of daily removal of BOD, ammonia and phosphorus vs. time in the control and in the presence of the aquatic plants. The initial rate of daily removal of BOD in the presence of plants (Figure 7a) ranged from 1.5 to 3 mgL^{-1}day^{-1} (day 1 and 2). In the absence of plants the corresponding results were 0.6 –1.1 mgL^{-1}day^{-1}. In the presence of plants the rate of ammonia removal (in day 1 and 2) ranged from 0.9 to 2.4 mgL^{-1}day^{-1}. In the control this rate vanished (Figure 7b, day 1–4). The same behavior was observed for the rate of phosphorus removal (Figure 7c). The general decline in the daily drop is characteristic of the BOD and ammonia in the presence of plants. The phosphorous and control of ammonia behaved differently showing even increase of the daily drop after day 4 (Figure 7c, *Eichhornia,* Figure 7b, control).



(a) (b)

Fig. 5: Results of test in the presence of *Ludvigia* and *Salvinia*:
(a) COD and total sewage dosage *vs.* time; (b) Turbidity (NTU) and total sewage dosage *vs.* time



(a) (b) (c) (d) (e) (f)

Fig. 6: Results of test in the presence of *Eichhornia crassipes* and *Pistia stratiotes*: (a) BOD *vs.* time; (b) COD *vs.* time; (c) TSS *vs.* time; (d) Turbidity *vs.* time; (e) ammonia *vs.* time; (f) phosphorus *vs.* time

Table 2: Decrease of Water Quality Indicators, after 11 Days, %

Indicators	*Eichhornia Crassipes*			*Pistia Stratiotes*			*Control*		
	Initial	*Final*	*Decrease, %*	*Initial*	*Final*	*Decrease, %*	*Initial*	*Final*	*Decrease, %*
BOD, mgL^{-1}	9.5	1.3	86.3	10.2	1.8	82.4	9.8	7.0	28.6
COD, mgL^{-1}	35.6	11.9	66.6	31.8	12.5	60.7	36.5	21.1	42.2
TSS, mgL^{-1}	15.5	0.5	96.8	14.5	0.5	96.6	16.5	1.5	90.9
Turbidity, NTU	6.7	0.7	89.6	5.9	0.9	84.7	6.2	1.3	79
Ammonia, mgL^{-1}	9.2	0.2	97.8	9.6	0.2	97.9	9.5	6.4	32.6
Phosphorus, mgL^{-1}	4.0	1.4	65	3.8	1.6	57.9	3.8	3.8	0

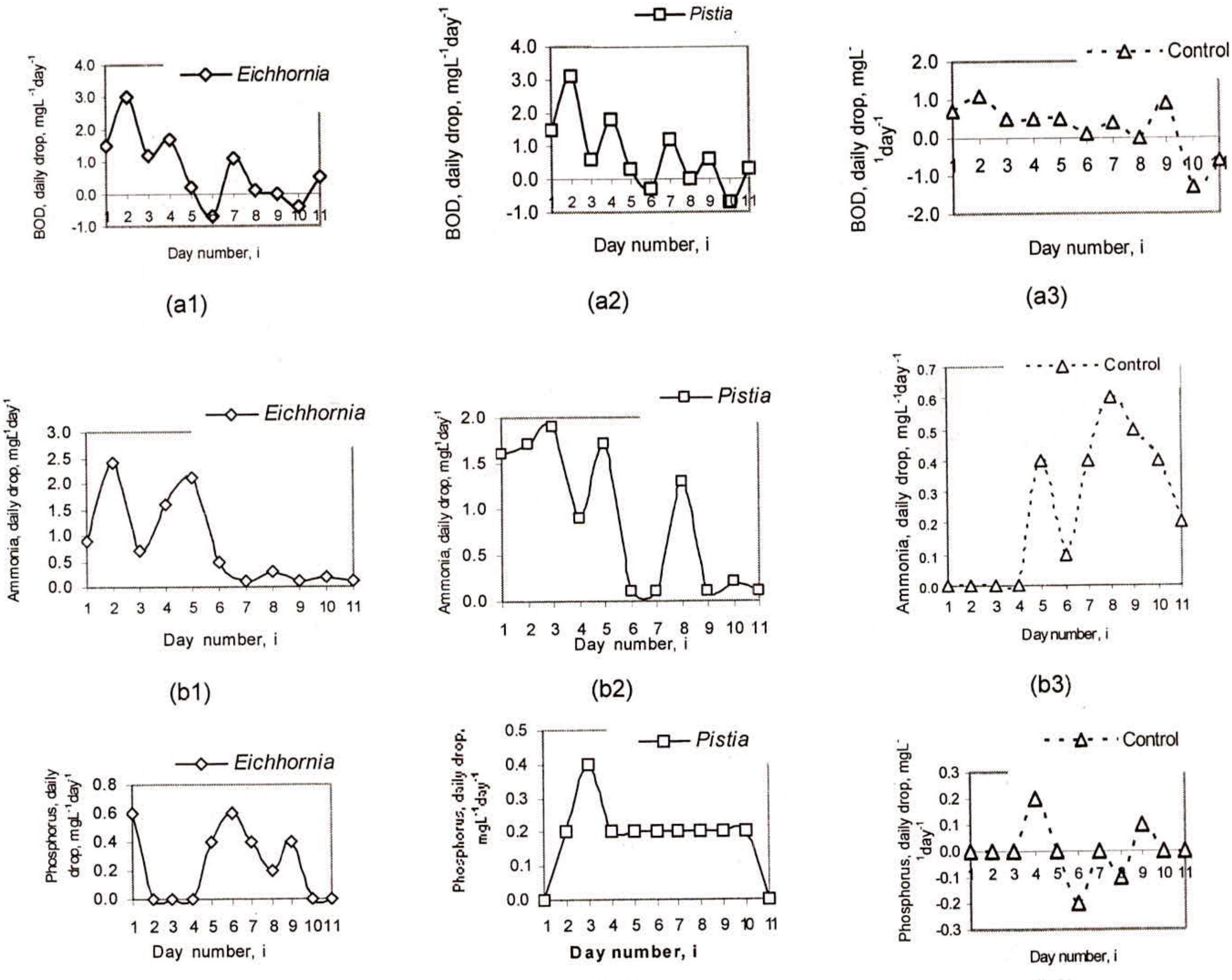
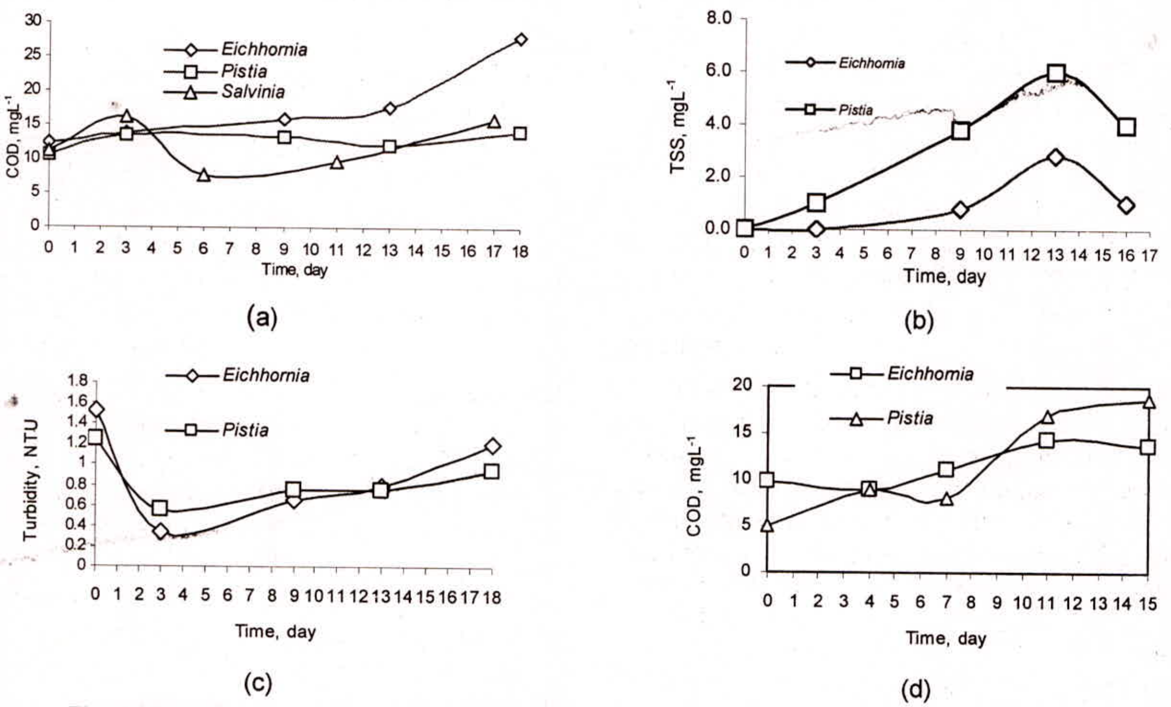


Fig. 7: Results of daily drop of the water quality indicators in the presence of *Eichhornia crassipes* and *Pistia stratiotes*:
(a) BOD vs. time: (a1) *Eichhornia crassipes,* (a2) *Pistia stratiotes*, (a3) control;
(b) ammonia vs. time: (b1) *Eichhornia crassipes,* (b2) *Pistia stratiotes*, (b3) control;
(c) phosphorus vs. time: (c1) *Eichhornia crassipes,* (c2) *Pistia stratiotes*, (c3) control

Set No. 5. Figure 8 depicts results of (a and d) COD, (b) TSS, and (c) turbidity vs. time. Figure 8 shows that the plants *Eichhornia crassipes, Pistia* and *Salvinia* are sources for fluctuations as well as increase of COD. The initial COD level ranged from 5 up to 12 mgL^{-1}, see Figure 8a and d. Five measurements indicated initial COD levels in the range 10–12 mgL^{-1} and one 5 mgL^{-1}. During 14 days, the COD levels in the presence of three plants tested fluctuated from 4 up to 18 mgL^{-1}. In day 15 a single result of 28 mgL^{-1} was recorded. Comparing these results with those obtained for diluted sewage, shows that in the latter all COD components originating from the sewage were virtually removed. This relies on the fact that the recorded lower bounds of COD agree with the COD levels which are typical of plants in fresh water. Thus, when the COD is lowered by a plant from, say, 30 mgL^{-1} to 15 mgL^{-1}, it can be safety assumed that practically, the COD level of the same plant in fresh water has been reached. Furthermore, fluctuations of the COD in a range around the lower bound is expected and ascribed to the effect of the plant. The lower bounds of the TSS and turbidity (Figure 6c, d) agree with the levels of those parameters for the tested plants in fresh water (Figure 8b, c). The TSS increased monotonically from 0 (at t = 0) to 2.8 mgL^{-1} (*Eichhornia*) and 6 mgL^{-1} (*Pistia*) in day 13, and then dropped back (day 16) to 1 and 4 mgL^{-1}, respectively.

The turbidity decreased from the initial levels of 1.24 and 1.53 NTU down to 0.3 and 0.5 NTU in day 3,



(a) (b)

(c) (d)

Fig. 8: Results of test in the presence of *Eichhornia crassipes, Pistia stratiotes* and *Salvinia*: (a) and (d) COD vs. time; (b) TSS vs. time; (c) Turbidity vs. time

rising to 1.0 and 1.2 NTU in day 18. These ranges of results conform with the lower bounds of purification of diluted sewage.

Outdoors Setup

A pilot unit for wastewater treatment by floating and emergent plants, was designed and constructed as a close circuit ecological system on the outskirts of the Civil and Environmental Eng. Dept. of the Technion (Figure 9). From left to right: greenhouse, floating and emergent plants sections. Emergent plants (green long leaves) is also seen growing from the bottom left.

Fig. 9: Pilot for wastewater treatment by aquatic plants

The dosage sequence is shown in Figure 10. The daily dosage of sewage was 2–2.3 m^3/day. An estimated total of 121 m^3 of wastewater was treated in this test. The plants were capable (under summer conditions, with air temperature up to 33°C) of holding the BOD below 20 mgL^{-1} (Figure 10). Notwithstanding the considerable changes and fluctuation of the feed and treated sewage quality, the pilot scale test confirmed the capacity of the plants to hold reasonably low levels of BOD. This demonstrated the effectiveness of this method for purification of sewage during the summer period.

DISCUSSION AND SUMMARY

Naturally growing aquatic macrophytes can be used to remove nitrogen, phosphorous, nitrates, phosphates and heavy metals, by consuming them in the form of plant nutrients (Agami and Reddy, 1991; Elifantz and Tel-Or, 2002; Tripathi *et al.*, 1991). An integrated pond system, consisting of duckweed and algae ponds, was investigated for treatment of anaerobically treated domestic wastewater (Van der Steen *et al.*, 1998). Fifty-six percent of the pond influent nitrogen, mainly ammonium, was removed.

Our laboratory experimental results confirm the capacity of aquatic plants *Eichhornia crassipes* and *Pistia stratiotes,* with a well developed root system, to further purify diluted sewage, with initially low levels

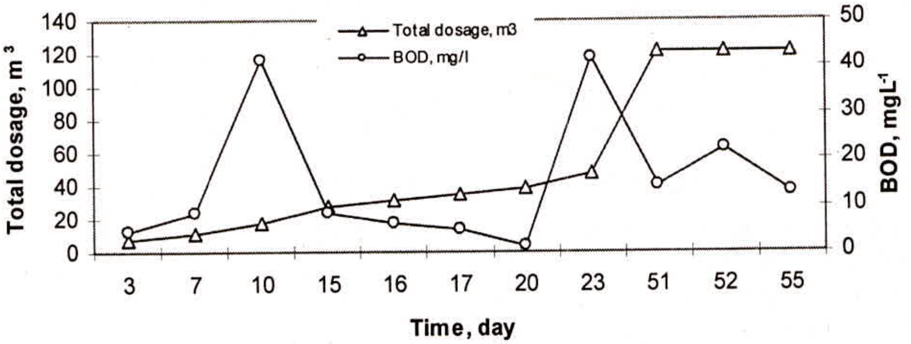


Fig. 10: Results of semi continuous sewage treatment in the pilot: total dosage and BOD vs. time

of the water quality indicators. Notwithstanding the considerable fluctuation of the feed and treated sewage quality, the laboratory scale tests in the presence of aquatic plants confirm their capacity to reach and hold exceptionally low levels of COD, TSS, ammonia, phosphorus and turbidity, i.e., when they are set to purify diluted sewage with initially low concentrations of the water quality indicators. This provides an idea of the lower bounds of the water quality indicators that can be reached in the presence of the aquatic plants tested. These lower bounds were confirmed by recording the levels of water quality indicators set by plants in fresh water. In the absence of pollutants that originate from the sewage, the level of water quality indicators changed as a sole effect of the plants. As these levels conform with the lower bounds recorded when diluted sewage was purified, they provide evidence that no further purification is feasible. This is due to death and decomposition of part of the plant roots and bacteria.

In low nutrient habitats water hyacinth can just maintain itself. The overall nutrient (such as P) requirement of water hyacinth is very low (Chadwick and Obeid, 1966; Reddy *et al*., 1990). This suggests that the plant can survive in low-P environment. It was shown experimentally that internal P cycling within water hyacinth plants, is adequate for its survival in low-P water (Reddy *et al*., 1990). However, if the plant nutrient concentration drops too low, then part of nutrients such as N and P will be lost with aged tissues (Arts, 1996).

Aquatic plants produced better kinetic features for sewage purification as compared to the control. This difference becomes more pronounced when the range of low levels of the water quality indicators is reached. In summary the present results confirm the capacity of a pulsed cascade of aquatic plants, *Eichhornia crassipes* and *Pistia stratiotes,* with circulation and a well developed root system, to further purify diluted sewage in shorter periods of time. The lower bounds for purification are set by the plants and not the sewage pollutants. This provides a novel approach for treatment of Israeli wastewater in order to meet stringent standards, regulations and reclamation standards of effluent quality, for example: BOD and TSS <5 mgL $^{-1}$, ammonia and phosphorus less than 0.5 and 1 mgL $^{-1}$, respectively (Rebhun, 2003). Removal of BOD, TSS and ammonia in our experiments complied with these requirements. It was shown that the aquatic plants were capable of overcoming changes in the feed while still maintaining the required levels of the measured water quality indicators (the BOD level was held below 20–22 mgL $^{-1}$).

ACKNOWLEDGEMENTS

This research is supported by the Keren Kayemeth LeIsrael, the Center for Absorption in Science, Ministry of Immigrant Absorption, State of Israel.

Most of the present work was published in "Water Environment Research" (Zimmels *et al*., 2007).

REFERENCES

Agami, M. and Reddy, K.R. (1991). Interrelationships between *Eichhornia crassipes* (Mart.) Solms and *Hydrocotyle umbellate* L. *Aquatic Botany*, 39, 147–157.

Aoi, T. and Hayashi, T. (1996). Nutrient removal by water lettuce (*Pistia stratiotes*). *Wat. Sci. Tech.* 34, 7–8, 407–412.

APHA, AWWA and WPFC (1995). *Standard Methods for the Examination of Water and Waste water,* American Public Health Association, 16th edition, Washington.

Arts, R. (1996). "Nutrient resorption from senescing leaves of perennials: are there general patterns?" *J. Ecol.* 84, 597–608.

Bishop, P.L. and Eighmy, T.T. (1989). "Aquatic wastewater treatment using *Elodea Nuttalli*." *Journal Water Pollution* Control Federation, 61, 641–648.

Boyd, C.E. (1974). "Utilization of aquatic plants. In: Mitchell, D.S. (Ed.)", *Aquatic Vegetation and Its Use and Control*. UNESCO, Paris, 107–115.

Brix, H. and Schierup, H.-H. (1989). "The use of aquatic macrophytes in water-pollution control." *Ambio,* 18, 100–107.

Casabianca, M.L.C. (1985). "Eichhornia crassipes: production in repeated harvest systems on waste water in the Languedoc region (France)." *Biomass,* 7 135–160.

Chadwick M.J. and Obeid, M. (1966). "A comparative study of the growth of *Eichhornia crassipes* Solms and Pistia stratiotes L. in water culture." *J. Ecol.* 54, 576–563.

Clough, K.S., DeBusk, T.A. and Reddy, K.R. (1987). "Model water hyacinth and pennywort systems for the secondary treatment of domestic wastewater." In: Reddy, K.R., Smith, W.H. (Eds.), *Aquatic Plants for Water Treatment and Resource Recovery*. Magnolia Publishing Inc., Orlando, FL, 775–781.

Costa, R.H.R., Bavaresco, A.S.L., Medri, W. and Philippi, L.S. (2000). "Tertiary treatment of piggery wastes in water hyacinth ponds." *Wat. Sci. Tech.* 42, 10–11, 211–214.

DeBusk, T.A., Peterson, J.E. and Reddy, K.R. (1995). "Use of aquatic and terrestrial plants for removing phosphorus from dairy wastewaters." *Ecol. Eng.* 5, 2–3, 371–390.

DeBusk, T.A., Ryther, J.H., Hanisak, M.D. and Williams, L.D. (1981). "Effects of seasonality and plant density on the productivity of some freshwater macrophytes." *Aquat. Bot.,* 10, 133–142.

de Casabianca-Chassany, M.-L., Boonne, C. and Bassères, A. (1992). "*Eichhornia crassipes* systems on three ammonium-containing industrial effluents (pectin, carcass-treatment wastes and manure): production and purification." *Bioresour. Technol.* 42, 2, 95–101.

Droste, R.L. (1997). *Theory and Practice of Water and Wastewater Treatment,* John Wiley & Sons, New York, 800.

Elifantz, H. and Tel-Or, E. (2002). "Heavy metal biosorption by plant biomass of the macrophyte *Ludvigia Stolonifera*." *Water, Air and Soil Pollution*, 141, 207–218.

Gersberg, R.M., Elkins, B.V., Lyon, S.R. and Goldman, C.R. (1986). "Role of aquatic plants in wastewater treatment by artificial wetlands." *Water Res.* 20, 363–368.

Jorgensen, S.E. (1994). "A general model of nitrogen removal by wetlands. In: Mitsch, W.J. (Ed.), Global Wetlands: *Old World and New*. Elsevier, Amsterdam, 575–583.

Kadlec, R.H. and Knight, R.L. (1995). *Treatments Wetlands*. Lewis Publisher, Boca Raton, USA.

Korner, 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." *J. Plankton Res.* 32,10 , 3092–3098.

Kumar, P. and Garde, R.J. (1990). "Upgrading wastewater treatment by water hyacinth in developing countries", *Wat. Sci. Tech.* 22, 153–160.

Mishra, P.C., Patri, M. and Panda, M. (1991). "Growth of water hyacinth and its efficiency in the removal of pollution load from industrial wastewater." *J. Ecotoxicol. Environ. Monit.* 1, 3, 218–224.

Mitsch, W.J. (1994). "The non-point source pollution control function of natural and constructed riparian wetlands. In: Mitsch, W.J. (Ed.), Global Wetlands." *Old World and New.* Elsevier, Amsterdam, 351–361.

Polprasert, C., Kessomboon, S. and Kanjanaprapin, W. (1992). "Pig wastewater treatment in water hyacinth ponds." *Water Sci. Tech.* 26, 9–11, 2381–2384.

Polprasert, C. and Khatiwada, N.R. (1998). "An integrated kinetic model for water hyacinth ponds used for wastewater treatment." *Water Res.* 32, 1, 179–185.

Reddy, K.R. (1983). "Fate of nitrogen and phosphorus in a wastewater retention reservoir containing aquatic macrophytes." *J. Environ. Qual.* 12, 137–141.

Reddy, K.R. and Sutton, D.L. (1984). "Water hyacinth for water quality improvement and biomass production." *Journal of Environmental Quality*, 13, 1–7.

Reddy, K.R., Sutton, D.L. and Bowes, G. (1983). "Freshwater aquatic plant biomass production in Florida." *Soil Crop Sci. Soc. Fla. Proc.* 42, 28–40.

Reddy, K.R. (1984). "Nutrient transformations in aquatic macrophyte filters used for water purification." In: *Proceeding on Future of Water Reuse.* Am. Water Works Assoc. 2, 660–678.

Reddy, K.R., Agami, M. and Tucker, J.C. (1990). "Influence of phosphorus on growth and nutrient storage by water hyacinth (Eichhornia crassipes (Mart.) Solms) plants." *Aquat. Bot.* **37**, 355–365.

Reddy, K.R. and DeBusk, W.F. (1985). "Nutrient removal potential for selected aquatic macrophytes." *J. Environ. Qual.* 19, 261–268.

Reddy, K.R. and DeBusk, T.A. (1987). "State-of-the-art utilization of aquatic plants in water pollution control." *Wat. Sci. Tech.* 19, 61–79.

Reddy, K.R. and Smith, W.H. (Eds.) (1987). *Aquatic Plants for Water Treatment and Resource Recovery*. Magnolia Publishing Inc., Orlando, FL, 1032.

Reed, S.C., Middlebrooks, E.J. and Crites, R.W. (1988). *Natural Systems for Waste Management and Treatment*. McGraw Hill, New York, 308.

Rebhun, M. (2003), "Comments to the effluent standards suggested by the Inbar Committee." *Water and Irrigation*, 436, 38–39. (In Hebrew).

Saha, S., (Das) and Jana, B.B. (2003). "Fish-macrophyte association as a low-cost strategy for wastewater reclamation", *Ecol. Eng.,* 21, 1, 21–41.

Sooknah, R.D. and Wilkie, A.C. (2004). "Nutrient removal by floating aquatic macrophytes cultured in anaerobically digested flushed dairy manure wastewater", *Ecol. Eng.*, 22, 1, 27–42.

Tchobanoglous, G., Maitski, F., Thompson, K. and Chadwick, T.H. (1989). "Evolution and performance of city of San Diego pilot scale aquatic wastewater treatment system using water hyacinths." *Research Journal of the Water Pollution Control Federation,* 58, 376–380.

Tripathi, B.D., Srivastava, J. and Misra, K. (1990). "Impact of pollution on the elemental composition of water hyacinth and duckweed in various ponds of Varanasi." *Sci. Cult.* 56, 327–330.

Tripathi, B.D., Srivastava, J. and Misra, K. (1991). "Nitrogen and Phosphorus Removal-capacity of Four Chosen Aquatic Macrophytes in Tropical Freshwater Ponds." *Environmental Conservation*, 18, 143–147.

US Environmental Protection Agency, Design Manual. 1988. *Constructed wetlands and aquatic plant systems for municipal wastewater treatment,* Office of Research and Development, Center of Environmental Research Information, Cincinnati, OH, p. 83.

US Environmental Protection Agency, 1993. *Subsurface flow constructed wetlands for wastewater treatment. A Technical Assessment.* Office of Water, Washington, DC.

Van der Steen, P., Brenner, Ash and Oron, G. (1998). "An integrated duckweed and algae pond system for nitrogen removal and renovation", *Wat. Sci. Tech.*, 38(1), 335–343.

Whitehead, A.J., Lo, K.V. and Bulley, N.R. (1987). "The effect of hydraulic retention time and duckweed cropping rate on nutrient removal from dairy barn wastewater." In: Reddy, K.R., Smith, W.H. (Eds.), *Aquatic Plants for Water Treatment and Resource Recovery.* Magnolia Publishing Inc., Orlando, FL, 697–703.

Wolverton, B.C. and McDonald, R.C. (1981). "Natural processes of treatment of organic chemical waste." *The Environmental Professional*, 3, 99–104.

Zimmels, Y., Kirzhner F. and Malkovskaja, A. (2007). "Lower bounds for extraction of pollutants from sewage by water plants". *Water Environment Research*, 79(3), 287–296.