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Nutrient Removal Potential of Selected Aquatic Macrophytes[1]

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ABSTRACT

The role of eight aquatic macrophytes in removing N and P from nutrient enriched waters was evaluated using microcosm retention ponds. The aquatic macrophytes included water hyacinth (*Eichhornia crassipes*), water lettuce (*Pistia stratiotes*), pennywort (*Hydrocotyle umbellata*), duckweeds (*Lemna minor* and *Spirodela polyrhiza*), azolla (*Azolla caroliniana*), salvinia (*Salvinia rotundifolia*), and a submersed macrophyte, egeria (*Egeria densa*). Nitrogen removal by aquatic macrophyte systems was in the order of water hyacinth > water lettuce > pennywort > *Lemna* > *Salvinia* > *Spirodela* > egeria during the summer season, while pennywort ranked first during the winter followed by water hyacinth, *Lemna*, water lettuce, *Spirodela*, *Salvinia*, and egeria. Phosphorus removal in summer was highest by water hyacinth and egeria systems, while pennywort and *Lemna* showed high P removal rates during the winter compared to other plants. Nitrogen and P removal were generally higher in summer than winter. Plant uptake accounted for 16 to 75% of total N removal, and 12 to 73% of total P removal, indicating the possibility of N and P removal by the mechanisms other than assimilation by plants.

Additional Index Words: water hyacinth, water quality, nitrogen, phosphorus, wastewater.

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Freshwater aquatic macrophytes grow naturally in water bodies polluted by nutrient loading from urban and agricultural activities. Many aquatic plants utilize these nutrients and produce large amounts of biomass which can be used for some beneficial purposes. The concept of using aquatic plants for treating wastewater is gaining the attention of local and state agencies in various parts of the USA (California, Florida, Mississippi, Louisiana, and Texas). Aquatic macrophyte systems can be effectively used to reduce pollutant levels in water bodies (Boyd, 1969; Lakshman, 1979; Wooten and Dodd, 1976; Wolverton and McDonald, 1979; Stowell et al., 1981; Reddy et al., 1982) and the biomass used for production of gaseous fuels (Shiralipour and Smith, 1984), feed (Bagnall et al., 1974), fiber (Nolan and Kirmse, 1974), and compost and organic soil amendments (Parra and Hortenstein, 1974).

Several studies have discussed the potential of aquatic plants for reducing N and P levels in wastewater (Wolverton and McDonald, 1979; Sutton and Ornes, 1975; Dunigan et al., 1975; Reddy, 1983), but most of these studies were limited to one plant, thus no comparative data among different plants grown under the same environmental conditions. The purpose of this study was to evaluate the role of different types of aquatic plants removing N and P from simulated wastewater. The results on relative growth rates of these plants cultured under identical conditions have already been reported elsewhere (Reddy and DeBusk, 1984; 1985). The purpose of this study is to establish the role of these plants in improving water quality.

MATERIALS AND METHODS

Aquatic plants evaluated in this study were obtained from the St. Johns River near Sanford, FL. Duplicate cultures of water hyacinth (*Eichhornia crassipes* (Mart) Solms), water lettuce (*Pistia stratiotes* L.), pennywort (*Hydrocotyle umbellata* L.), water ferns (*Azolla caroliniana* and *Salvinia rotundifolia* L.), duckweeds (*Lemna minor* L. and *Spirodela polyrhiza* L.), and egeria (*Egeria densa* Planch) were maintained in 1000-L concrete tanks (1.7-m^2 water surface area)

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Table 1. Average solar radiation and ambient air temperature during summer and winter growing seasons (1982–1983).

Environmental variables	Summer	Winter
Solar radiation, MJ m^{-2} day^{-1}	17.8 ± 4.2	9.6 ± 4.1
Temperature, °C		
Average	27.3 ± 1.3	14.0 ± 3.8
Minimum	22.3 ± 1.2	8.6 ± 4.6
Maximum	32.2 ± 1.9	19.4 ± 3.7

placed outdoors. Tanks containing small plants (duckweeds and water ferns) were filled with only 700 L of simulated wastewater, while the remaining plants were cultured in tanks with 900 L of simulated wastewater. Initial concentrations of N and P in the simulated wastewater were 26 to 29 mg N L^{-1} (equal proportion of NH_4 and NO_3) and 3.1 to 3.4 mg P L^{-1}, respectively. In addition to N and P, water also contained 25 mg K L^{-1}, 62 mg Ca L^{-1}, 0.6 mg Fe-EDTA L^{-1}, and micronutrients. Azolla was cultured in N-free nutrient medium. Micronutrients were applied through commercially available liquid fertilizer (nutrispray-Sunniland, Chase and Co., Sanford, FL) to obtain a final concentration of 4 mg Fe L^{-1}, 1.5 mg Mn L^{-1}, 0.2 mg Cu L^{-1}, 0.04 mg B L^{-1}, 0.02 mg Mo L^{-1}, and 3 mg S L^{-1}. The simulated wastewater in each tank was mixed by submersible pumps which operated on a 12-h cycle. Once a week, water in each tank was replaced with fresh water having the same original chemical composition.

To monitor the growth of large-leaf floating plants (water hyacinth, pennywort, and water lettuce), and submersed plant (egeria), two baskets with polyvinyl chloride (PVC) frame and Vexar mesh (0.25 m^2 surface area) were placed in each tank. Starting plant density was the same both inside and outside the PVC baskets. At the end of each week, Vexar mesh baskets were removed from the tanks, allowed to drain for 5 min, weighed, and returned to the respective tanks. This procedure was repeated once a week until maximum plant density was observed and no additional growth was recorded. For small-leaf floating plants (azolla, salvinia, and duckweed), two 0.25-m^2 floating PVC frames were placed in each tank, and the same starting plant density was maintained both inside and outside the PVC frames. At the end of each week, plants inside the PVC frames were removed, allowing the excess water to drain. After weights were recorded, plants were returned to respective PVC frames. Plants were harvested only when maximum plant density was observed and no measurable net growth was recorded. Subsamples were taken from the area outside the PVC frame, dried to a constant weight at 70°C, and dry weights determined. A constant dry weight was obtained in 72 h.

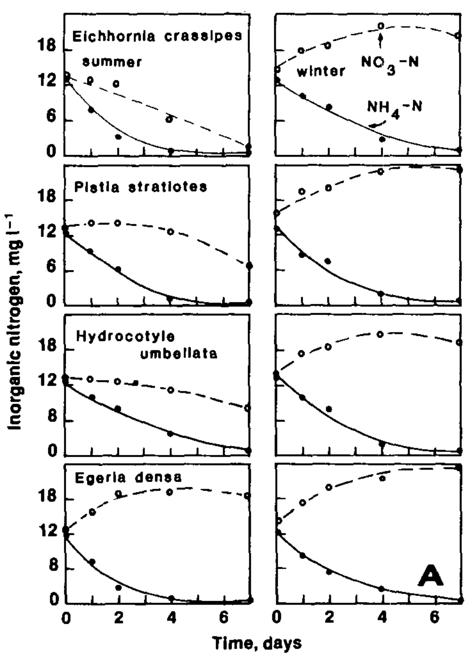

Fig. 1a. Changes in NH_4^+ and NO_3^- concentrations of the water in the systems containing large-leaf floating plants. Data points represent an average of all plant densities encountered within summer or winter growing seasons. Each data point shown represents an average of 24 values in summer and 20 values in winter.

Intensive water sampling was conducted for a period of 16 wks in the summer of 1982 (June–September) and for 12 wks in winter 1982 through 1983 (December–February). Average ambient air temperature and solar radiation at the study site are shown in Table 1. Water samples were obtained at 0, 1, 2, 4, and 7 d during each detention period and analyzed for NH_4^+, NO_3^-, and PO_4^{3-} (APHA, 1982). Once a week, pH and dissolved O_2 were measured. Plant samples were obtained at the end of each harvest and analyzed for N and P. Dissolved O_2 was measured by an O_2 meter (Yellow Springs Instruments, Yellow Springs, OH), while pH was measured by a standard combination pH electrode and pH meter.

RESULTS AND DISCUSSION

Dissolved O_2 content of the water under large-leaf floating plants was low (2.4–3.9 mg L^{-1}). Dissolved O_2 of the water in these experimental systems was increased by mixing water with submersible pumps. Dissolved O_2 content of the lakes, rivers, and ponds containing dense cover of floating plants is usually much lower than those observed in these experimental systems (Rai and Munshi, 1979). In an egeria system, O_2 content of the water was found to be highest (8.1 mg L^{-1}). This was expected because submersed macrophytes release O_2 as a result of imbalance between photosynthesis and respiration (Bouldin et al., 1974). The pH of the water was not significantly influenced by the type of floating macrophyte, but the submersed macrophyte system showed slightly alkaline pH conditions.

Changes in water N and P concentrations in aquatic macrophyte systems are shown in Fig. 1a, 1b, and 2. These data represent average values for all plant densities observed during the summer or winter growing season (Reddy and DeBusk, 1984, 1985). Ammonium N was rapidly lost from all systems both in summer and winter, with concentration decreasing from 12.7 mg N L^{-1} to 0.5 mg N L^{-1}. Rapid disappearance of NH_4^+ was probably the result of active nitrification, as evidenced by an increase in NO_3^- concentration of the water.

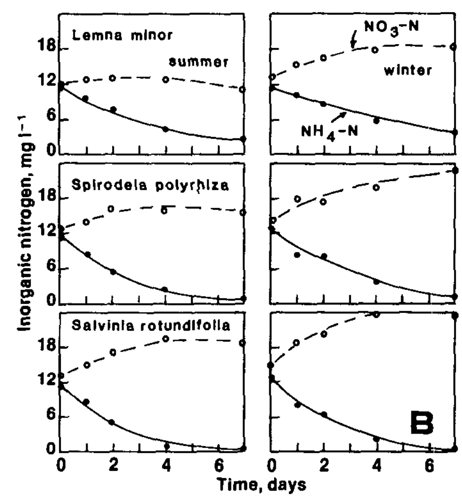

Fig. 1b. Changes in NH_4^+ and NO_3^- concentrations of the water in the systems containing small-leaf floating plants. Data points represent an average of all plant densities encountered within summer and winter growing seasons. Each data point shown represents an average of 24 values in summer and 20 values in winter.

Nitrate concentration of the water in summer months increased steadily during the first 2 d of residence time, followed by a decrease towards the end of the 7-d residence period. Nitrification was also found to be active during winter months, resulting in poor net removal of NO_3^- from the system. During winter months, NO_3^- concentration of water increased by about 33% at the end of the 7-d residence period. Since pH of the water was < 7.0, it is unlikely that any significant amount of NH_4^+ was lost due to volatilization (Stratton, 1969).

Most of the NH_4^+ removal in the systems containing small-leaf floating plants was also due to nitrification (Fig. 1b). Nitrate removal by small-leaf floating plants was very poor, especially during winter months. Egeria (submersed plant) was very effective in NH_4^+ removal during both summer and winter. Average NH_4^+ concentration in the water decreased from 12.1 mg N L^{-1} to 0.56 mg N L^{-1} in 7 d. Decrease in NH_4^+ removal reflected a direct increase in NO_3^- concentration, indicating active nitrification. Although it was previously shown (Reddy, 1983) that the egeria system would increase water pH by about 2 to 3 units and create favorable conditions for NH_3 volatilization, rapid nitrification during this study prevented any loss of N through volatilization. The overall inorganic N removal by this system was poor. It should be noted that in our study, plants were cultured in a system containing no underlying sediment, thus reducing N loss due to denitrification. Under natural conditions, NO_3^- formed in the water would diffuse into the underlying sediment and undergo denitrification (Engler and Patrick, 1974).

Phosphorus concentration of the water decreased rapidly during the 7-d residence time (Fig. 2). During the summer months, 67 to 93% of the added P was lost in 7 d, while during winter months, 57 to 69% of the added P was removed. Maximum P removal of 93% occurred in the water hyacinth system during summer, followed by 67 and 74% P removal by water lettuce and pennywort, respectively. Maximum P removal of about 69% was observed in the pennywort system during winter months. Water P concentration in systems containing small-leaf floating plants decreased rapidly from about 3.3 mg P L^{-1} to 1.1 mg P L^{-1}, both in summer and winter.

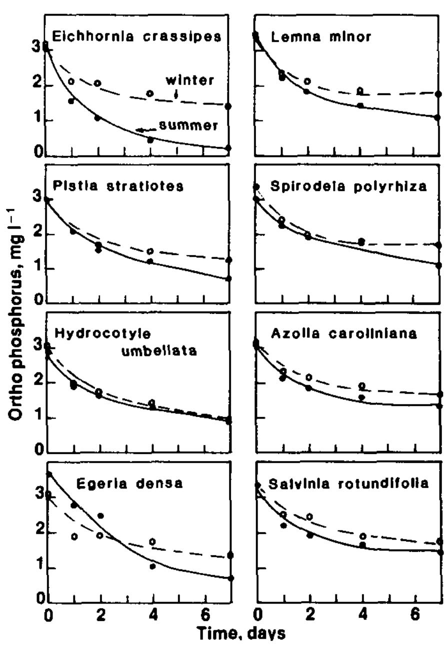

Fig. 2. Changes in soluble P concentration of the water as affected by plant type and growing season. Data points represent an average of all plant densities encountered within summer and winter growing seasons. Each data point shown represents an average of 24 values in summer and 20 values in winter.

Table 2. Nitrogen and phosphorus content of the plants during two growing seasons (1982–1983).

Plant type	Nitrogen June–September	Nitrogen December–February	Phosphorus June–September	Phosphorus December–February
	g kg^{-1} of plant tissue			
Water hyacinth	30.5 ± 3.4	35.3 ± 2.9	5.8 ± 0.9	6.8 ± 1.1
Water lettuce	36.2 ± 5.2	40.3 ± 3.4	8.0 ± 1.1	11.2 ± 1.5
Penneywort	42.4 ± 2.3	45.1 ± 5.1	10.5 ± 1.6	9.9 ± 1.9
Duckweed (*Lemna minor*)	51.2 ± 2.5	54.1 ± 2.1	15.2 ± 1.9	14.2 ± 2.2
Duckweed (*Spirodela polyrhiza*)	48.6 ± 0.8	51.8 ± 2.0	11.0 ± 0.7	13.1 ± 1.2
Salvinia	34.7 ± 8.9	32.1 ± 7.7	9.0 ± 2.2	10.7 ± 1.1
Azolla	27.7 ± 4.3	34.1 ± 1.4	8.4 ± 2.8	7.3 ± 1.6
Egeria	35.6 ± 3.1	40.3 ± 4.7	13.7 ± 1.7	12.8 ± 1.6

Nitrogen and P concentrations of the plant tissue were found to be generally higher in winter than summer (Table 2). Low tissue N and P concentrations during summer were probably due to dilution as a result of more biomass per unit area. During winter, high tissue N and P concentrations probably resulted from slow growth and luxury uptake (Reddy et al., 1983). Azolla cultured in N-free medium accumulated about 35 g N kg^{-1} of plant tissue, primarily due to symbiotic N_2 fixation through an *Azolla-Anabaena* symbiotic relationship (Peters et al., 1980).

Potential N and P removal rates by aquatic macrophytes are presented in Table 3. Values in column A represent the removal rates due to plant uptake alone.

Table 3. Potential nitrogen and phosphorus removal by aquatic macrophyte systems operated at a 7-d detention period.

	Nitrogen				Phosphorus			
	Summer		Winter		Summer		Winter	
Plant type	A†	B‡	A	B	A	B	A	B
	mg m^{-2} day^{-1}							
Water hyacinth	1278	3276	254	551	243	371	49	252
Water lettuce	985	2759	258	434	218	297	72	205
Penneywort	365	2025	370	777	86	240	81	265
Duckweed (*Lemna minor*)	292	946	70	450	87	234	18	205
Duckweed (*Spirodela polyrhiza*)	151	740	135	353	34	139	34	248
Azolla	108	–	48	–	33	128	10	135
Salvinia	406	873	96	208	105	217	32	203
Egeria	125	581	121	161	48	410	38	202

† A = calculated using the growth rate in the linear phase of the growth curve and average tissue N and P contents. This represents N and P removal due to plant uptake alone.

‡ B = calculated using the N and P concentrations in the water. This represents N and P removal due to plant uptake and due to nutrient transformations.

This was estimated by multiplying the growth rate obtained in summer and winter by respective N and P concentrations in the plant tissue. Values shown in column B represent the N removal by the whole system. This was calculated by using the N and P concentrations of the water. Although plant uptake played a significant role in the removal of N and P, it did not account for all of the N and P loss from the system, indicating the possibility of biochemical (denitrification and microbial assimilation) and physico-chemical (volatilization of NH_3) processes functioning in the system. Plant uptake accounted for 18 to 39% of total N removal in summer, and 16 to 75% of total N removal in winter. Phosphorus removal due to plant uptake was higher (12 to 73% of total P removal) in summer, as compared to winter (9 to 35% of total P removal). Significant NO_3^- accumulation indicates the possibility of nitrification and NO_3^- can be potentially lost due to denitrification in anoxic zones. Nitrogen loss due to denitrification probably would be of greater magnitude if anaerobic sediment was present in the experimental systems. Phosphorus loss appears to be due to chemical precipitation since the tap water used contained high concentrations of Ca (48 mg L^{-1}) and Mg (10 mg L^{-1}). The significance of these processes needs further investigation.

Results presented in this study show that aquatic macrophytes can be effectively used in reducing the N and P levels of nutrient enriched waters. Water hyacinth showed the highest N removal rate (3.3 g N m^{-2} d^{-1}) in summer compared to the other aquatic plants. During winter, pennywort was more effective in N removal (0.8 g N m^{-2} d^{-1}), than (0.6 g N m^{-2} d^{-1}) during the summer time. Pennywort is a cool season plant and is the most dominant species found in many freshwater bodies of Florida during winter months, while water hyacinth is severely affected by freezing temperatures. High growth rates and N removal capacity of pennywort in winter and water hyacinth in warm growing seasons suggest that these plants can be alternatively cultured during wi winter and summer to maintain the treatment system efficiency at maximum level. Nitrate removal rate by small-leaf floating plants and submersed macrophyte are low and these plants are not suitable for monoculture in ponds used for water treatment. However, these plants can be effectively cultured in polyculture systems along with large-leaf floating plants to enhance the nutrient removal capacity or to alter the physicochemical environment. For example, water hyacinth and azolla, or water hyacinth and egeria can be cultured in series of ponds where water hyacinth pond will effectively remove N while the second pond containing azolla or egeria would maximize P removal (Reddy et al., 1982). At low plant densities water hyacinth and duckweed or water hyacinth and azolla can be grown in the same pond to maximize N and P removal efficiency. The economic feasibility of these systems in wastewater renovation, especially using water hyacinth and emergent plants such as cattail (*Typha latifolia* L.) and reed (*Phragmites* spp.) are currently being tested in pilot scale projects in sun-belt states.

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