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Productivity and Nutrient Uptake of Water Hyacinth, *Eichhornia crassipes* I. Effect of Nitrogen Source[1]

K. R. REDDY AND J. C. TUCKER[2]

Water hyacinth, Eichhornia crassipes, *growth and nutrient uptake rates, as influenced by different N sources and N transformations, were measured using microcosm aquaculture systems. Net productivity was highest in the system receiving equal amounts of* NH_4^+ *and* NO_3^- *(at 10 mg N* l^{-1} *each) and decreased in the order of* NO_3^-, NH_4^+, *urea (added at 20 mg N* l^{-1} *each), and methane digestor effluent (at 6 mg N* l^{-1}*). During the first 7-wk study (average ambient air temperature was 26–28°C), biomass yields were in the range of 19–53 g dry wt* m^{-2} day^{-1}*, while between the 8th and 12th wk (average ambient air temperature was 16–22°C), biomass yields were in the range of 10–33 g dry wt* m^{-2} day^{-1}*. In the systems with either* NH_4^+ *or* NO_3^-*, or both added in equal proportions, about 14–20% of the total yield was contributed by roots, whereas in the system with urea and digestor effluent, roots contributed about 23 and 44% of the total yield, respectively. Nitrogen and P uptake per unit area followed trends similar to biomass yields. Nitrogen uptake rates were in the range of 533–2,161 mg N* m^{-2} day^{-1} *for the systems receiving* NH_4^+, NO_3^-*, and urea, while uptake rates were in the range of 124–602 mg N* m^{-2} day^{-1} *for the system receiving methane digestor effluent. Phosphorus uptake rates were found to be in the range of 59–542 mg P* m^{-2} day^{-1}*. Under the most favorable conditions, maximum recorded biomass yield was 53 g dry wt* m^{-2} day^{-1}*, with N and P removal rate of 2,161 mg N* m^{-2} day^{-1} *and 542 mg P* m^{-2} day^{-1}*, indicating the potential of water hyacinth to produce large amounts of biomass which can be potentially used as a feedstock to produce methane.*

In the past, most vascular aquatic plants were considered a nuisance in water bodies. However, there is growing interest in the potential use of some aquatic plants (Boyd, 1970) for wastewater purification and use of the resulting biomass for production of energy, feed, fiber, and other products. As a result, several researchers have begun to study the growth, physiology, and nutritional requirements of these plants in greater detail. Water hyacinth, *Eichhornia crassipes* (Mart) Solms, is the most commonly used vascular aquatic plant in renovating sewage effluents (Ornes and Sutton, 1975; Rogers and Davis, 1972; Wolverton and McDonald, 1979) and agricultural drainage effluents (Reddy et al., 1982). Currently, in the United States, several research projects are in progress to evaluate the potential use of water hyacinth as a feedstock for methane production. In order to use water hyacinth as a feedstock for producing energy, a large constant supply of biomass is needed.

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TABLE 1. AMBIENT AIR AND WATER TEMPERATURES DURING THE STUDY PERIOD.

Week no.	Date	Ambient air temperature[a] Min	Max	Average	Water[b] temperature
		°C			
1	01/17/81–09/24	19.2	37.1	28.2	—
2	09/24–10/01	18.9	37.5	28.2	—
3	10/01–10/08	17.4	38.9	28.2	28.4
4	10/08–10/15	19.8	36.5	28.2	25.3
5	10/15–10/22	14.7	36.2	25.5	25.4
6	10/22–10/29	18.4	36.0	27.2	27.4
7	10/29–11/05	19.4	32.7	26.1	—
8	11/05–11/12	15.0	28.9	22.0	23.2
9	11/12–11/19	7.6	32.7	20.2	19.8
10	11/19–11/25	7.5	27.4	17.5	19.8
11	11/25–12/03	13.3	31.7	22.5	22.7
12	12/03–12/10	5.0	27.0	16.0	17.2

[a] Average of 7 days.
[b] Average of 12 tubs taken 1 day/wk.

The productivity of water hyacinth cultured in nutrient enriched waters and wastewaters was found to be in the range of 40–88 m t (dry wt) ha^{-1} yr^{-1} (Yount and Crossman, 1970; Ryther et al., 1978; Wolverton and McDonald, 1979; Reddy and Bagnall, 1981). The quality and productivity of water hyacinth is dependent on the available nutrient supply. Under most conditions, N is probably the major plant nutrient limiting productivity. Growth and nutrient uptake of water hyacinth are also controlled by the source of N (e.g., NH_4^+, NO_3^-, urea, or organic N). Shiralipour et al. (1981) observed that N supplied through foliar application of urea produced maximum water hyacinth biomass as compared to $(NH_4)_2CO_3$ or KNO_3. Tucker (1981) showed that an increased rate of N application to a water hyacinth system not only increased the yield of water hyacinth, but also produced plants of greater nutritive value. Reddy (1983) using ^{15}N techniques, observed no difference in productivity and N uptake when plants were supplied with both NH_4^+ and NO_3^- in the same system. Studies reported in the literature on the effect of N source did not consider the effect of N processes involved in converting one form of N to another form. The objectives of this study were to evaluate the effect of N source and N transformations on the growth and uptake of nutrients (N and P) by water hyacinth cultured under managed systems.

MATERIALS AND METHODS

Growth and nutrient uptake of water hyacinth were monitored in 300-*l* aquaculture systems (Reddy,1983). This system essentially consisted of a tank (120 × 60 × 60 cm) lined with a layer of 6 mil polyethylene sheet. The tanks were placed in a greenhouse where air temperature was maintained by cross ventilation at approximately the same level as encountered outside the greenhouse. Maximum and minimum ambient air temperatures are given in Table 1. Water in the tubs was continuously mixed by a submersible pump. This study was initiated on 17 September 1981, and continued for a period of 12 wk.

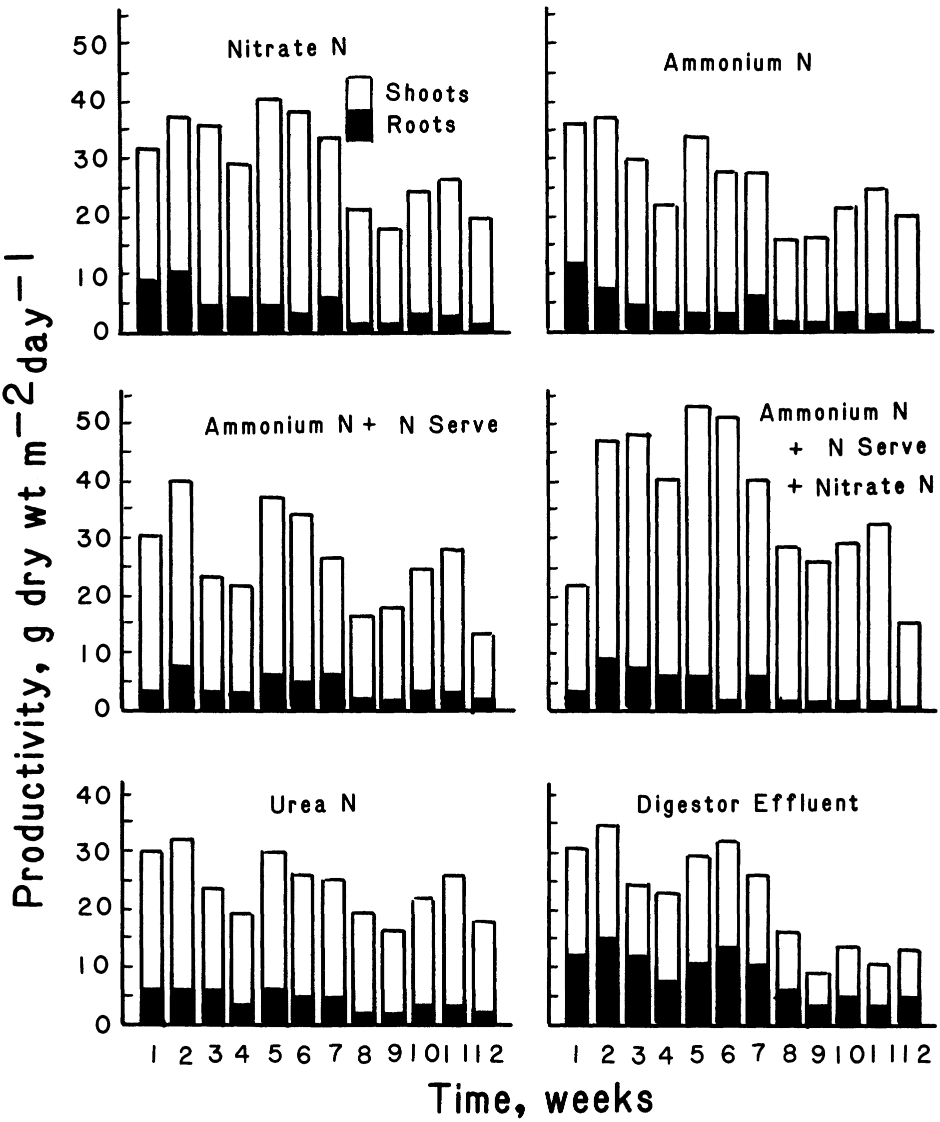

Fig. 1. Net productivity of water hyacinth as influenced by nitrogen source and ambient air temperature at a water exchange rate of 7 days.

Water hyacinth plants were collected from the St. Johns River. All plants were trimmed of dead and unhealthy leaves. Two 0.5 m^2 Vexar mesh baskets were placed in each tank with each basket receiving the same number of plants at a rate of 9.1 kg wet wt m^{-2}. Chemical composition of the water was equivalent to 10% Hoagland solution minus N and P, and initial P concentration of the water was 5 mg P l^{-1} added as KH_2PO_4. There were 2 replications for each treatment. Different sources of N as described below were added to each container:

1. Nitrate N as KNO_3 added at 20 mg N l^{-1}.
2. Ammonium N as NH_4Cl added at 20 mg N l^{-1}.
3. Ammonium N as NH_4Cl at 20 mg N l^{-1} + N-serve (2 chloro-6-trichloromethyl)

TABLE 2. VOLATILE SOLIDS AND ASH CONTENT OF THE PLANT TISSUE AS INFLUENCED BY NITROGEN SOURCE.[a]

N-source	Volatile solids		Ash	
	Shoots	Roots	Shoots	Roots
	% (dry wt basis)			
1. Nitrate N	78.0	76.7	22.0	23.3
2. Ammonium N	82.7	81.9	17.3	18.1
3. Ammonium N + N-serve	83.2	83.0	16.8	17.0
4. Ammonium N + N-serve + nitrate N	78.0	78.1	22.0	21.9
5. Urea N	80.5	79.4	19.5	20.6
6. Digestor effluent	79.3	76.7	20.7	23.3

[a] N-serve = 2-chloro-6-(trichloromethyl) pyridine added at a rate of 5 mg ℓ^{-1}.

pyridine). N-serve was added at a rate of 5 mg l^{-1} to prevent NH_4^+ oxidation to NO_3^-.

4. Ammonium N as NH_4Cl at 10 mg N l^{-1} + N-serve plus nitrate as KNO_3 at 10 mg N l^{-1}.
5. Urea N as urea at 20 mg N l^{-1}.
6. Methane digestor effluent added at 6 mg N l^{-1}.

In treatments 1–5, the water from each tank was drained every 7 days and replaced with fresh nutrient solution containing its respective N source. For treatment 6, a known volume of methane digestor effluent was added once a week to the same water. The effluent used in the study was the discharge of a methane digestor which was fed 5 days a week with chopped water hyacinth. The chemical composition of effluent was determined each week. Once a week the Vexar cages containing the plants were remov.ed from the tank and allowed to drain for 4 min and weighed. The plants were then harvested to their original starting density and at the same time plant samples were obtained. For each plant, roots and shoots were separated, subsequently dried at 70°C for 48 h, and analyzed for plant nutrients. Water samples were obtained at 0, 3, and 7 days of each week and analyzed for NH_4^+, NO_3^-, total Kjeldahl N, and ortho-P. Dissolved O_2 and pH were measured each week. Water loss per week was measured for each treatment and also for control tanks containing no plants.

Dissolved O_2 was measured by a YSI oxygen meter; pH was monitored by a glass electrode. Ammonium and NO_3^- were analyzed on an autoanalyzer. Total Kjeldahl N in plant tissue and water was determined by digestion followed by steam distillation (Bremner, 1965). Soluble ortho-P was determined by the ascorbic acid reduction method (A.P.H.A., 1971). Plant samples were digested with nitric-perchloric acid, and P in the digested samples was determined by the ascorbic acid reduction method using the autoanalyzer.

RESULTS

Plant biomass yields

Data in Fig. 1 show the shoot and root biomass yields of water hyacinth as influenced by different sources of N. Net productivity was highest in the treatments receiving equal amounts of NH_4^+ and NO_3^-, and decreased in the order

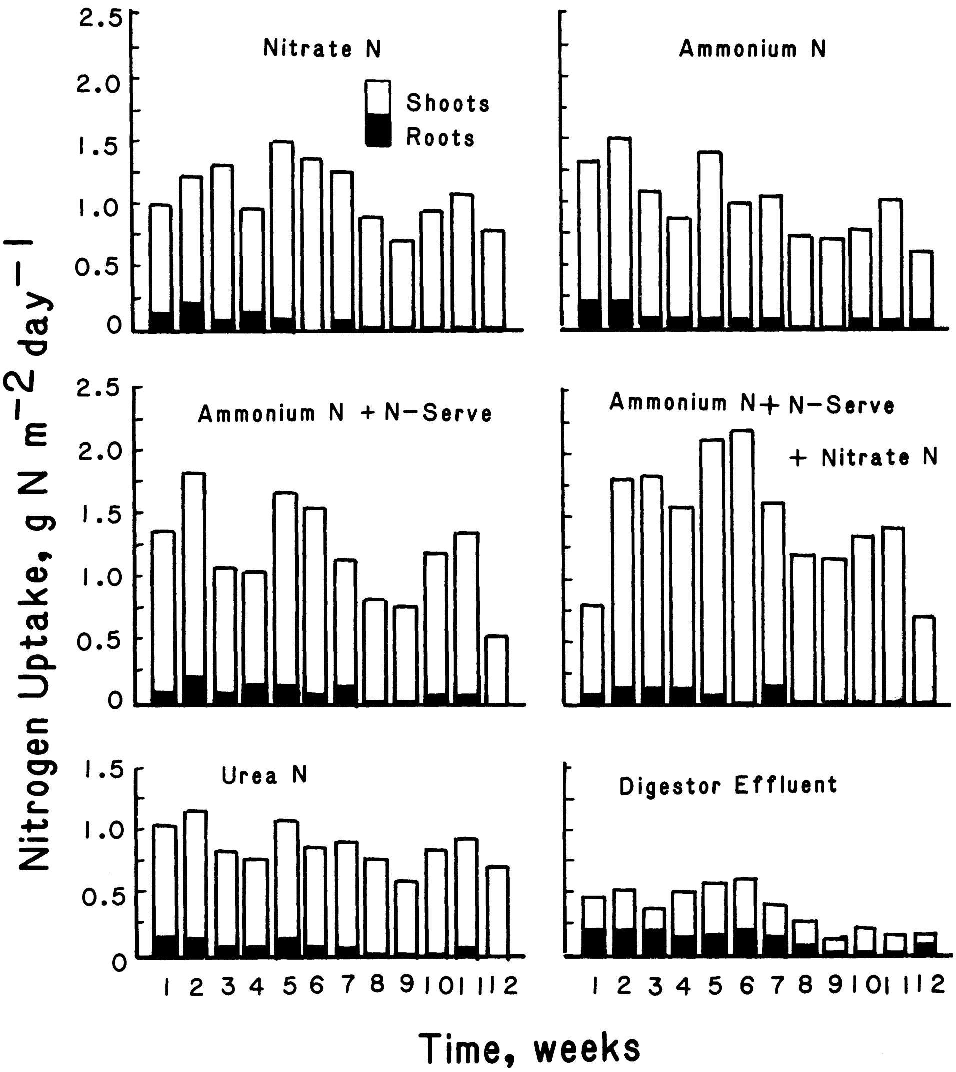

Fig. 2. Nitrogen uptake by water hyacinth as influenced by nitrogen source and ambient air temperature at a water exchange rate of 7 days.

of treatments receiving NO_3^-, NH_4^+, urea, and methane digestor effluent. Maximum biomass production of 53 g dry wt m^{-2} day^{-1} was recorded during the 5th wk in the treatment receiving NH_4^+ plus N-serve and NO_3^-. During the first 7 wk of study, average ambient air temperatures were approximately the same (26.1–28.2°C). Biomass yields during this period were in the range of 22–53 g dry wt m^{-2} day^{-1} for treatments receiving NH_4^+ plus NO_3^-, NH_4^+, or NO_3^-. During the same period, treatments receiving urea N and digestor effluent N recorded slightly lower biomass yields (19–34.4 g dry wt m^{-2} day^{-1}). Differences among treatments were more striking between the 8th and 12th wk of the study period when average ambient air temperatures were in the range of 15.7–21.9°C. Biomass yields decreased significantly during this period, as compared to the first 7 wk of this

TABLE 3. MASS BALANCE OF ADDED NITROGEN IN A WATER HYACINTH SYSTEM.

N-source	Plant uptake			Water	
	Shoots	Roots	Total	Ammonium	Nitrate
	% of added nitrogen				
1. Nitrate N	35.7 ± 8.6	4.5 ± 2.2	40.2 ± 8.9	0.94 ± 0.90	58.9 ± 8.9
2. Ammonium N	33.0 ± 6.7	4.3 ± 1.9	38.4 ± 7.9	4.3 ± 7.0	57.8 ± 7.8
3. Ammonium N + N-serve	41.1 ± 6.9	4.9 ± 1.7	46.0 ± 7.9	52.8 ± 7.9	1.3 ± 0.7
4. Ammonium N + N-serve + nitrate N	52.0 ± 8.7	4.8 ± 2.0	56.8 ± 9.3	2.1 ± 2.8	41.1 ± 7.9
5. Urea N	25.6 ± 3.4	4.3 ± 1.2	29.9 ± 4.1	0.75 ± 0.70	69.4 ± 4.2

study. Drastic reduction in biomass yields during the weeks with cooler temperatures was observed in the treatment receiving digestor effluent. Digestor effluent contained significant quantities of organic N and mineralization of organic N was probably functioning at a slower rate during the weeks with cooler temperatures, thus reducing the inorganic N availability to the plants.

Shoot yields of water hyacinth were in the range of 10.4–49.1 g dry wt m^{-2} day^{-1} for the treatements receiving NH_4^+ plus NO_3^-, NH_4^+ or NO_3^-, while the treatment with urea recorded 13.1–25.4 g dry wt m^{-2} day^{-1}. Shoot yields were significantly lower in the treatment receiving digestor effluent (5.4–19.5 g dry wt m^{-2} day^{-1}). The shoot/root weight ratio was in the range of 4.2 to 6.5 for treatments with NH_4^+ plus NO_3^-, NH_4^+ or NO_3^-, 3.7 for the treatment with urea, and 1.3 for the treatment with digestor effluent. Contribution of root biomass to the total yield was controlled by the amount of available N in the water. In the system with readily available N (NH_4^+ or NO_3^-) contribution of root biomass to the total yield was in the range of 14.1–19.8% of the total yield, whereas in the system with urea and digestor effluent (less available N) contribution of root biomass was 22.7 and 44.3% of the total yield, respectively.

Ash content of the plant tissue was lower in the plants cultured in solutions containing NH_4^+ as compared to the plants grown in solutions containing NO_3^- (Table 2). Differences among N sources may not be as significant, if the dry matter yields were adjusted to their ash content. Shoots generally contained less mineral matter than roots.

Plant uptake of nitrogen

Plants cultured in the water with NH_4^+ source of N recorded high N concentration (4.2–4.9%) in the shoots compared to the plants cultured in the systems with NO_3^-, urea (3.9–4.1%), or digestor effluent N (1.7%). The shoot portion of the plant contained about 2 times as much N as roots of the plants cultured in the system containing readily available N (NH_4^+, NO_3^-, or urea), while approximately the same amounts of N were present in the shoots and roots of plants grown in digestor effluent. Nitrogen concentration of the plant tissue was not influenced by the average ambient air temperature (15.7–28.2°C).

Uptake of N by water hyacinth plants followed trends similar to plant biomass yields (Fig. 2). Uptake rates in the range of 691–2,161 mg N m^{-2} day^{-1} were recorded by the plants cultured in the water containing equal amounts of NH_4^+ and NO_3^-, and N uptake rates decreased in the order of the systems containing

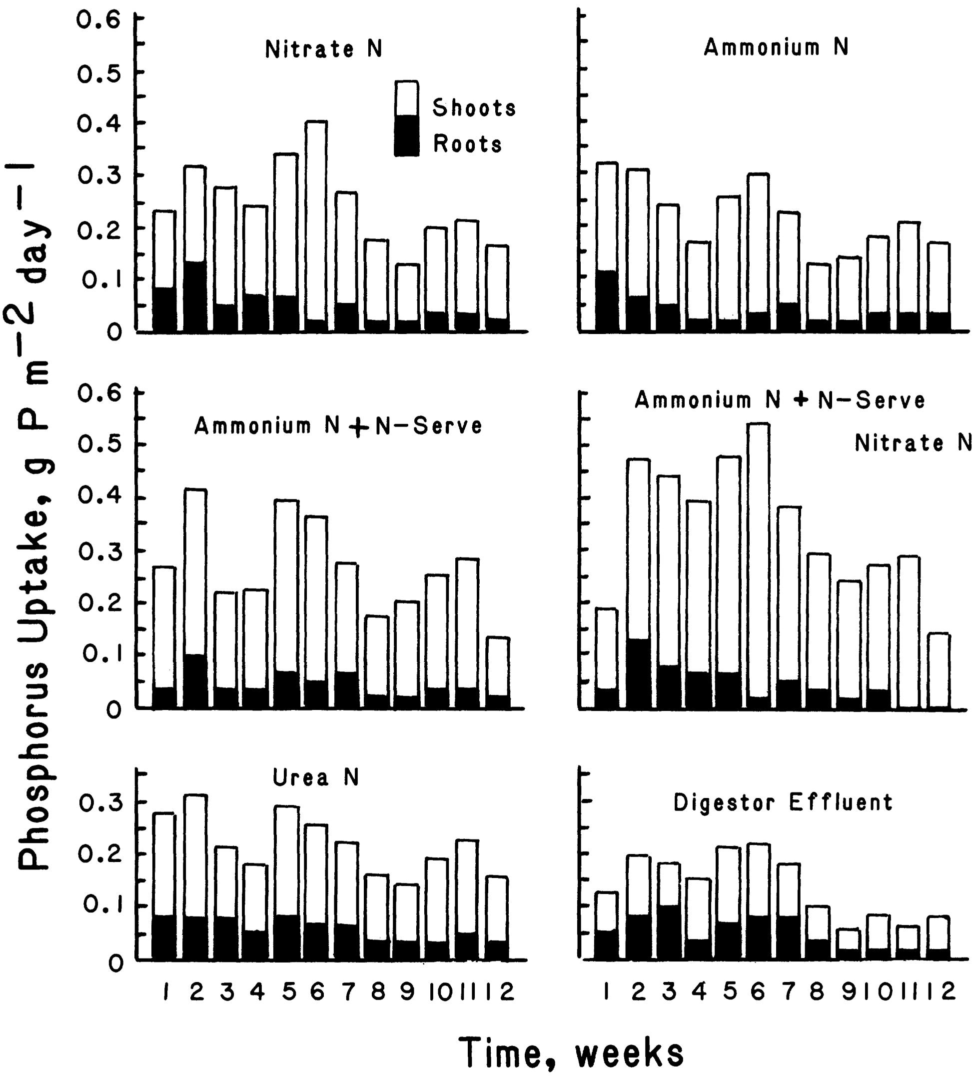

Fig. 3. Phosphorus uptake by water hyacinth as influenced by nitrogen source and ambient air temperature at a water exchange rate of 7 days.

NH_4^+ plus N-serve (533–1,818 mg N m^{-2} day^{-1}), NO_3^- (707–1,484 mg N m^{-2} day^{-1}), NH_4^+ (618–1,499 mg N m^{-2} day^{-1}), urea (610–1,155 mg N m^{-2} day $^{-1}$), and digestor effluent (124–602 mg N m^{-2} day^{-1}). Nitrogen uptake rates were higher during the first 7-wk period when average ambient air temperature was in the range of 26.1–28.2°C, as compared to the period (8–12th wk) when average ambient air temperatures were in the range of 15.7–21.9°C.

In the systems with readily available N (NH_4^+, NO_3^-, or urea), about 87–92% of the total N uptake by plants was recovered in the shoots. Shoot/root N uptake ratios were 11.9, 8.8, 8.3, 7.1, 6.7, and 1.4 for the treatments containing NH_4^+ plus N-serve and NO_3^-, NH_4^+ plus N-serve, NO_3^-, NH_4^+ with no N-serve, urea and digestor effluent, N, respectively.

TABLE 4. WATER LOSS (MM DAY $^{-1}$) IN A SYSTEM CONTAINING WATER HYACINTH PLANTS.

N-source	Water loss Total	Storage in plants	Evapotranspiration
	mm day^{-1}		
1. Nitrate N	5.3 ± 1.0	0.57 ± 0.14	4.7 ± 0.9
2. Ammonium N	5.1 ± 1.2	0.50 ± 0.13	4.6 ± 1.1
3. Ammonium N − N-serve	5.3 ± 1.0	0.50 ± 0.16	4.8 ± 0.9
4. Ammonium N + N-serve + nitrate N	6.0 ± 1.5	0.69 ± 0.24	5.3 ± 1.3
5. Urea	4.8 ± 1.4	0.50 ± 0.10	4.3 ± 1.3

Data on mass balance of added N (Table 3) indicate that about 38–57% of the added N was removed by the plants during the 7-day residence time in the systems containing NH_4^+ or NO_3^-, while only 30% of the added N was recovered in the plants cultured in the water-containing urea N. Plant recovery of added N was higher from the system containing NH_4^+ and N-serve, compared to the systems containing NH_4^+ with no N-serve. In all systems, about 41–69% of the added N was still present in the water at the end of 7-day residence time.

Plant uptake of phosphorus

Phosphorus concentration of the plant tissue was not significantly influenced by the source of added N. Generally, shoots contained less P (0.62–0.99% P) than the roots (0.66–1.39% P). Phosphorus concentration of the plant tissue was not influenced by the average ambient air temperature (15.7–28.2°C). Uptake of P by water hyacinth generally followed trends similar to N uptake and dry matter yields (Fig. 3). Plants cultured in the water containing both sources of N (NH_4^+ + N-serve and NO_3^- N) recorded highest P uptake rates (144–542 mg P m^{-2} day^{-1}), followed by the systems containing NH_4^+ plus N-serve (132–396 mg P m^{-2} day^{-1}), NO_3^- (125–398 mg P m^{-2} day^{-1}) urea (143–313 mg P m^{-2} day^{-1}), and digestor effluent (59–219 mg P m^{-2} day^{-1}). The rate of P uptake was higher in plants cultured at an average ambient air temperature of 26.1–28.2°C, compared to the plants cultured at 15.7–21.9°C.

The P distribution in shoots and roots was also influenced by the N sources. In the systems with the added NH_4^+ or NO_3^-, about 16–23% of the total P uptake remained in the roots, while 77–84% of the total P uptake was translocated to the shoots. In the systems with urea and digestor effluent about 32 and 44% of the total P uptake, respectively, were recovered in the roots, while 56 and 68% of the total P uptake, respectively, were translocated to the shoots. Shoot/root uptake ratios were 5.4, 4.0, 3.5, 3.4, 2.2, and 1.3 for the treatments containing NH_4^+ plus N-serve and NO_3^-, NH_4^+ plus N-serve, NO_3^-, NH_4^+ with no N-serve, urea, and digestor effluent, respectively.

Water loss

Data on water loss due to evapotranspiration by water hyacinth plants are shown in Table 4. Water loss was directly related to the dry matter yields. Water loss due to evapotranspiration was in the range of 4.3–5.3 mm day^{-1} (88–91% of the total water loss), whereas 0.5–0.7 mm day^{-1} (9–12% of the total water loss)

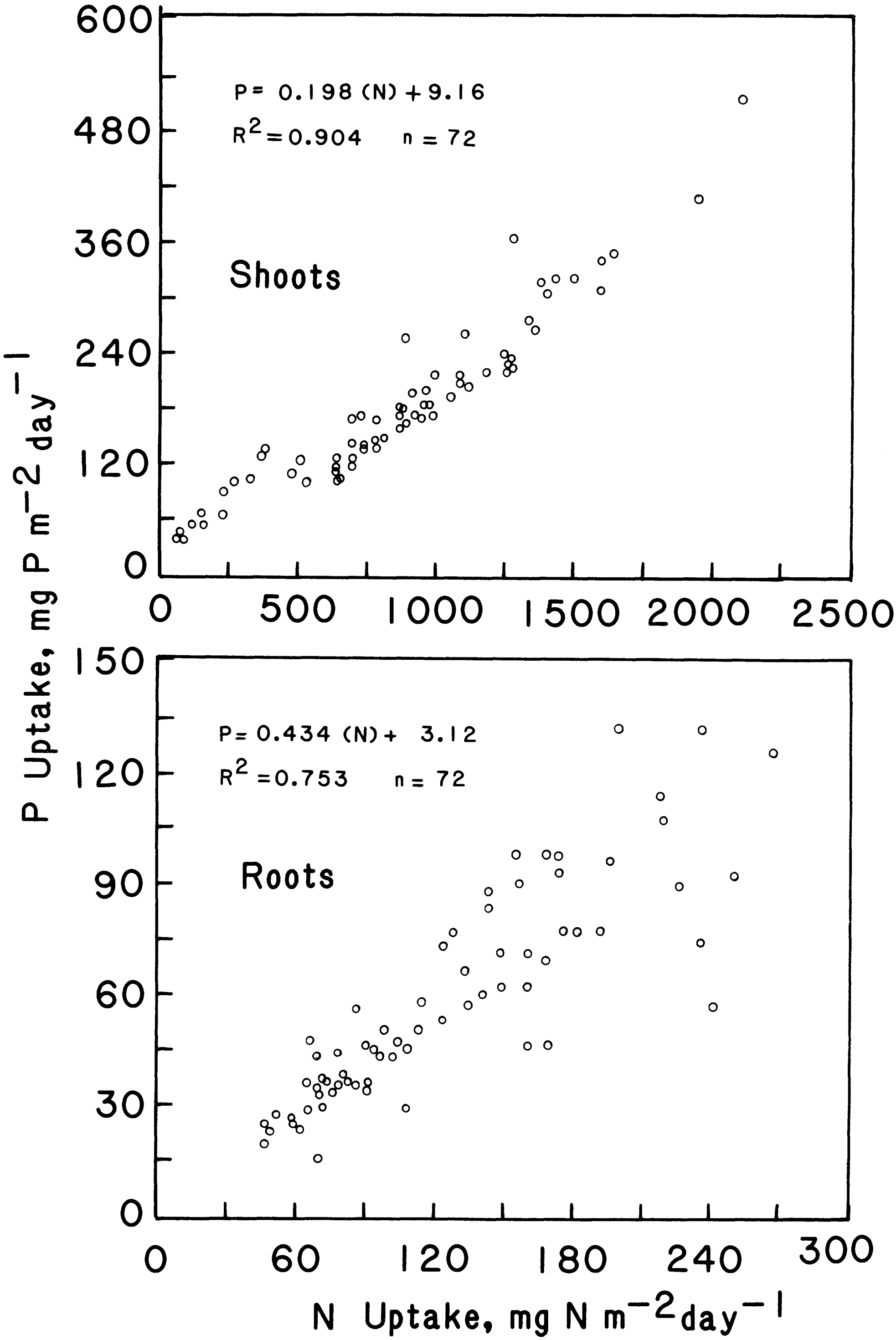

Fig. 4–5. Relationship between nitrogen and phosphorus recovery in shoots and roots as influenced by nitrogen sources.

was stored in the plant tissue. Water loss due to evaporation was 1.8 mm day^{-1}, indicating about 3-fold water loss from the system containing plants.

DISCUSSION

Results obtained in this study indicate that addition of NH_4^+ and NO_3^- to the water can improve biomass yields and N and P uptake of water hyacinth more than addition of any other single N source. Urea and digestor effluent were found to be less effective in improving biomass yields and N and P uptake by plants. Tucker (1981) observed higher dry matter yields of water hyacinth cultured with NO_3^- than with a NH_4^+ source; however, when the yields were expressed on an ash free basis, dry matter yields did not differ significantly. Results obtained in our study indicate that water hyacinth was more efficient in utilizing the NH_4^+ than NO_3^- when both forms of N were supplied in equal proportions in the same system (Table 3). In the treatment containing 10 mg NH_4^+-N l^{-1}, plants absorbed primarily NH_4^+ during the 7-day residence time, leaving most of the added NO_3^- in the water. Only 2.1% of the added N was recovered in the water as NH_4^+, while about 41% of the added N was recovered from the water as NO_3^-. Most of this NO_3^- was derived from the initially added NO_3^- since NH_4^+ oxidation to NO_3^- was prevented by N-serve. Dissolved O_2 and pH of the water in all systems were in the range of 2.5–7.1 mg l^{-1} and 6.3–7.3, respectively, indicating favorable conditions for microbial activity. Therefore, the disappearance of NH_4^+ from the water confirms the preferential plant uptake of NH_4^+ over NO_3^-. Under these conditions about 56.8 ± 9.3% of the added N was removed through plant uptake. The role of N-serve in improving biomass yields and N and P uptake needs further investigation. It is possible that pyridine compound added through N-serve was absorbed by water hyacinth roots, but in this study such evidence is not available. Further studies in our laboratory have demonstrated that addition of NH_4^+ and NO_3^- in equal proportions without addition of N-serve also produced similar biomass yields as compared to the system receiving N-serve.

Water hyacinth exhibited maximum P uptake of 542 mg P m^{-2} day^{-1} when cultured in the system containing equal amounts of NH_4^+ and NO_3^-, while uptake rates were lower when the plant was supplied with either NH_4^+, NO_3^-, or urea. In a recent study, Shiralipour et al. (1981) observed that P concentrations of the plant tissue were increased when plants were supplied with increased concentration of urea through foliar application. In our study, P uptake by water hyacinth was slower in the systems containing 20 mg N l^{-1} as urea, as compared to the other ionic forms of N. Although urea hydrolysis to NH_4^+ and nitrification were completed in 7 days, plants were probably stressed for inorganic N at the beginning of each 7-day residence period, thus resulting in lower biomass yields and P uptake.

A highly significant correlation was observed between N and P uptake rates (Fig. 4, 5) by water hyacinth. Nitrogen recovery in the shoots was about 5.1 times more than the P recovery, while N recovery in the roots was about 2.3 times the P recovery. These relationships suggest that during plant uptake of nutrients, proportionately more N was translocated to the shoots than P. These data also suggest that optimum N/P ratio in water medium should be in the range of 2.3–5 to achieve maximum biomass yields. The linear relationships shown in Fig.

4 and 5 can be used to estimate P removal rates by using data on N uptake rates. The maximum biomass yield of 53 g dry wt m^{-2} day^{-1}, observed during the most favorable conditions of the study, is equivalent to a potential biomass yield of 193 m t ha^{-1} yr^{-1} (86 tons $acre^{-1}$ yr^{-1}). Maximum N and P uptake rates under these conditions were found to be 2,161 mg N m^{-2} day^{-1} and 542 mg P m^{-2} day^{-1}, respectively. This represents an annual potential removal rate of 7,887 kg N ha^{-1} yr^{-1} and 1,978 kg P ha^{-1} yr^{-1} from wastewaters.

ACKNOWLEDGMENTS

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