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Nutrient Removal by Waterhyacinth[1]

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Abstract. Removal of nitrogen and phosphorus by waterhyacinth [*Eichhornia crassipes* (Mart.) Solms] in static and flowing water was investigated. Milligrams of phosphorus absorbed per plant per day in static water averaged 1.1, 2.1, 3.1, and 1.6 in 10, 25, and 50% Hoagland's solution and in sewage effluent, respectively, while in flowing water the values were 1.7, 2.5, and 3.3 for 10, 25, and 50% Hoagland's solution. Milligrams of nitrogen absorbed per plant per day from these same solutions averaged 5.3, 11.4, 19.8, and 6.6 from static water and 9.9, 18.4, and 20.8 from flowing water. Transpiration per plant per day averaged approximately 175 ml in static water and 225 ml in flowing water. One hectare of waterhyacinth plants under optimum conditions could absorb the average daily nitrogen and phosphorus waste production of over 800 people.

Introduction

One form of water pollution is eutrophication. This is the process of enrichment of natural waters by plant nutrients. It is undesirable when nutrients stimulate excessive aquatic plant production which renders the water nonpotable, unsuitable for recreational purposes, or not navigable (5, 9). Oxygen deficits and taste and odor problems of water are often associated with over-production of algae in eutrophic water. The abatement of eutrophication is often costly using existing technology. Probably the most effective solution is to remove fertilizing agents, especially nitrogen and phosphorus, from effluent before they enter lakes and streams (4, 11). It has been proposed that certain aquatic plants might be used for eliminating nutrients (2, 7, 17). Such plants would be grown on effluents, thereby removing nutrients before the effluents were released into natural waters. The plants would then be harvested and used as feed, green manure, or disposed of in some other manner. Several workers have suggested the possible use of waterhyacinth for the cleanup of effluents and have pointed out several advantages of using this plant (2, 15, 17). For a plant to be useful in pollution abatement it needs to be prolific; Penfound and Earle (12) reported that 10 waterhyacinth plants may produce 655,360 plants in a single growing season. Since they float, they may be easily harvested; in fact, equipment for their removal has already been constructed (10). The species flourishes in water heavily enriched with sewage effluent (14). From extensive studies of aquatic plant contents, Boyd (2) has estimated that 1 ha of waterhyacinth grown for 1 year could remove the annual nitroten waste of 500 persons and the phosphorus waste of 225 persons.

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Materials and Methods

Absorption of nitrogen and phosphorus by waterhyacinth was measured in a static water system and a continuous flow system. Environmental conditions were held constant for all experiments. Day temperature was 30 C and night 24 C. A light intensity of 11,000 lux was supplied by two cool white fluorescent tubes during the 12-hr light period. Relative humidity ranged from 40 to 70%. Plants were grown on full Hoagland's solution prior to use. Uniform sized plants were trimmed of dead parts; their roots were rinsed in the solution in which they were to be grown and drained for 30 sec. Plants were weighed and placed in the containers used in the experiment. Four solutions were used: 10, 25, and 50% Hoagland's solution as recommended by Gerloff (6) and secondary sewage effluent obtained from a treatment plant maintained by the City of Auburn, Alabama. The phosphorus and nitrogen contents of the sewage effluent were 3.6 and 22 mg/L, respectively. This was very close to the concentrations present in 10% Hoagland's solution which were 3 and 22 mg/L, respectively.

Static water experiments. In one experiment (A) single waterhyacinth plants were placed in 1.9 L of treatment solution contained in 2-L Nalgene beakers for 4 days. Twelve beakers were used for each solution; nine of these contained plants and three were without plants and served as controls. Weight of each beaker and its content was taken at the beginning and end of each light period to determine evapotranspiration in light and dark. Nutrient samples were taken from each beaker at the beginning and end of the experiment and filtered through a standard glass filter (Gelman type A) (3). Dissolved solids were estimated with a Myron L dissolved solids meter. The readings obtained were converted to mg/L by multiplying by a factor obtained by comparing the readings obtained on various strengths of Hoagland's solution with the known composition of these solutions. The aminonaphtholsulfonic acid method was used for phosphorus determinations (1). Nitrogen was determined by nesslerization following micro-Kjeldahl digestion (1). In a second experiment (B) five waterhyacinth plants were placed in 9.0 L of treatment solution contained in 13-L plastic dish pans for 4 days. Twelve dish pans of each solution were prepared; nine contained plants and three served as controls. Thus, each treatment was replicated three times. Evapotranspiration was measured by daily weighings. Nutrient samples were taken daily, filtered, and assayed for nitrogen, phosphorus, and dissolved solids as in the single plant study.

Continuous flow experiment. The continuous flow apparatus consisted of a 20-L supply reservoir, a trough containing plants, and a fraction collector (Figure 1). Nutrient solution entered the trough from the supply reservoir at one end, traveled the length of the trough, and was collected in 2.5-L increments at the other end. Nine experi-

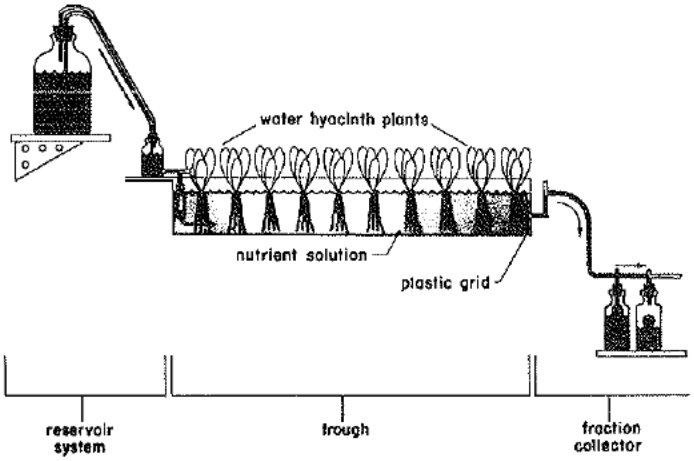

Figure 1. Apparatus used for the study of nutrient absorption by waterhyacinth from a continuously flowing nutrient source.

ments were conducted; three each with 10, 25, and 50% Hoagland's solution. Thirty waterhyacinth plants were used in each experiment. The flow rate was 20 ml/min, and 60 L of solution were maintained in the trough. Times for runs ranged from 50 to 70 hr. The first 2.5-L fraction and alternate ones thereafter were assayed for nitrogen, phosphorus, and dissolved solids as in the static water experiments. Evapotranspiration was assumed to be the difference between solution inflow and outflow.

The reservoir system consisted of a 20-L bottle connected to a 1-L bottle by a siphon tube and back-suction tube in such a manner as to maintain an almost constant solution level and, hence, hydrostatic pressure in the bottle. A needle valve at the bottom of the bottle controlled flow rate. Solution entered the trough via a glass sleeve to prevent surface disturbances. The trough was constructed of 1.9-cm plyboard lined with a double layer of 6-mil polyethylene; and its dimensions were: length, 170.5 cm; top width, 30 cm; bottom width, 17 cm; and depth, 23 cm. The outlet tube of the trough led to a movable plastic cylinder which served as a leveling device (Figure 1). A plastic screen prevented plant roots from obstructing the outlet. Tygon tubing led from the cylinder top to the fraction collector. The collector consisted of twelve 2.5-L glass reagent bottles, each containing a soft rubber ball 3.2 cm in diameter. The ball served as a floating valve. Each bottle was fitted with a rubber stopper with a cross-shaped piece of glass inserted through it. The arms of the crosses were connected with Tygon tubing, thus joining adjacent bottles. The upright portion of the cross served as an air inlet while the bottom portion led into the bottle. As the sample was collected, the ball floated up into the bottle neck, and closed off that bottle. Successive bottles were filled in the same manner.

Algal contaminations are of major concern in aquatic nutrient studies (8). Algal growth was minimized in our studies by maintaining high densities of waterhyacinth and thus of shade. Waterhyacinth leaves have a strong tendency to interlock. Care was taken to prevent this when containers were moved since whenever petioles are bent the leaf blades soon begin to die.

Results and Discussion

Static water experiments. Daily water losses were similar in the two static water experiments (Table 1 and Figures 2 to 5). There was no difference in rate of water loss be-

Table 1. Daily averages of water lost and nitrogen, phosphorus, and dissolved solids (DS) absorbed by waterhyacinth in various experimental designs.[a]

Experiment		Nutrient		H_2O lost[b]	Absorption[b]		
Type	Plants/ container	Status	Source		P	N	DS
				(L)	(mg)	(mg)	(mg)
A	1	Static	10% H	0.15 b	1.1 d	5.8 c	33.2 b
A	1	Static	25% H	0.18 b	2.2 b	11.8 b	32.0 b
A	1	Static	50% H	0.23 a	3.1 a	21.8 a	65.2 a
A	1	Static	SE	0.18 b	1.6 c	7.0 c	24.2 b
B	5	Static	10% H	0.14 c	1.1 d	4.7 c	0.7 c
B	5	Static	25% H	0.17 ab	2.0 b	11.0 b	21.7 b
B	5	Static	50% H	0.19 a	3.0 a	17.8 a	64.2 a
B	5	Static	SE	0.16 bc	1.6 c	6.1 c	29.5 b
C	30	Flowing	10% H	0.22 a	1.7 b	9.9 b	48.0 b
C	30	Flowing	25% H	0.19 a	2.5 b	18.4 a	87.9 a
C	30	Flowing	50% H	0.17 a	3.3 a	20.8 a	104.1 a

[a]Values in experiments A and B are averages of nine replications and for experiment C are averages of three replications. The values 10, 25, and 50% H are fractions of full-strength Hoagland's solution and SE is sewage effluent.
[b]Values within a given type of experiment and in the same vertical column are not significantly different at the 5% level when followed by the same letter.

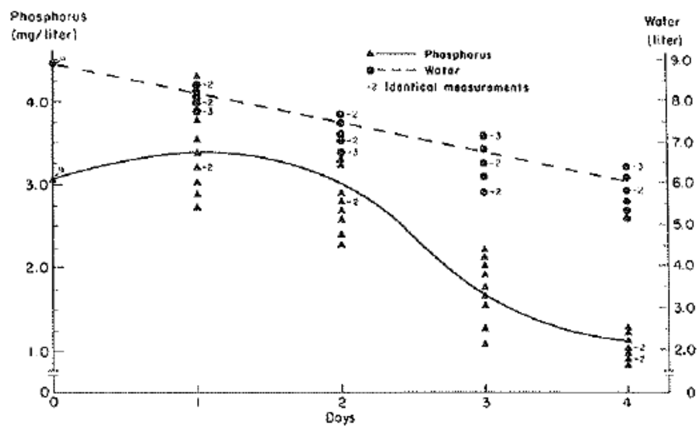

Figure 2. Effect of growing five waterhyacinth plants for 4 days in 10% Hoagland's solution (Experiment B) on the amount of water remaining and its phosphorus concentration. Calculated regression equation for phosphorus concentration: $Y = 1.04 + 3.20X - 1.26X^2 + 0.12X^3$.

tween plants grown in sewage effluent and those grown in 10% Hoagland's solution, and the rate was about 163 ml/plant per day in the single plant study (A) and 150 ml/plant per day in the multiple plant study (B). The differences in water loss between the experiments may be accounted for by the higher humidity that built up among the plants grown in groups. The most water was lost from plants grown in 50% Hoagland's solution, and the greater loss was probably a result of the more rapid growth of waterhyacinth in these solutions. Approximately 70% of the total evapotranspiration occurred during the 12-hr light period, and water loss was 5.3 times greater from containers with plants than from those without (tabular data not included). This is somewhat higher than the values obtained in a field study by Timmer and Weldon (16) who found that water loss through evapotranspiration from waterhyacinth was 3.7 times that from open water.

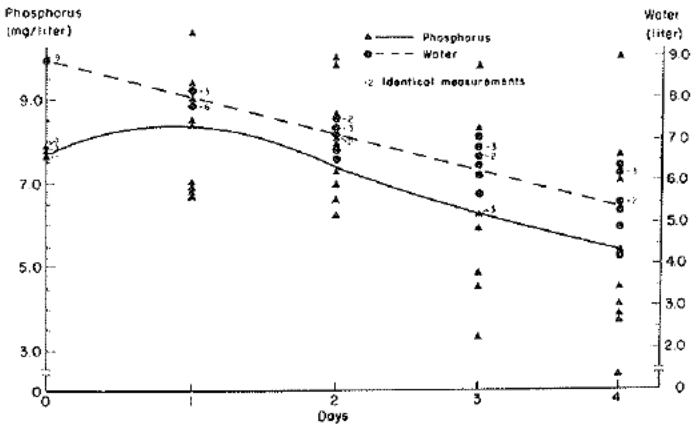

Figure 3. Effect of growing five waterhyacinth plants for 4 days in 25% Hoagland's solution (Experiment B) on the amount of water remaining and its phosphorus concentration. Calculated regression equation for phosphorus concentration: $Y = 4.75 + 4.36X - 1.60X^2 + 0.15X^3$.

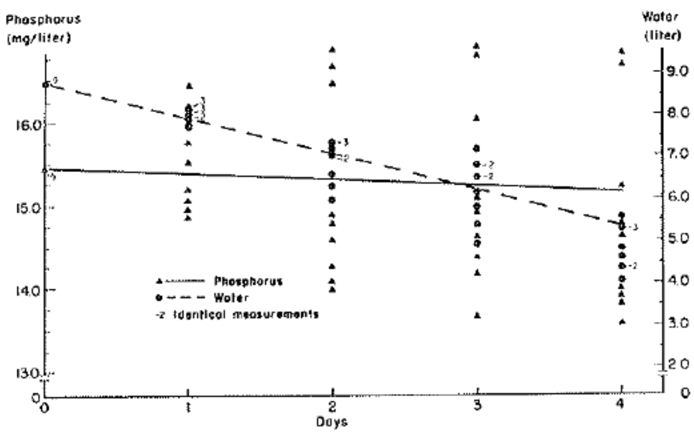

Figure 4. Effect of growing five waterhyacinth plants for 4 days in 50% Hoagland's solution (Experiment B) on the amount of water remaining and its phosphorus concentration. Calculated regression equation for phosphorus concentration: $Y = 15.5 - 0.08X$.

Penfound and Earle (12) reported a figure of 3.2. Both of these studies were done with dense masses of plants, so evapotranspiration may have been decreased somewhat by the close proximity of plants. The high rate of evapotranspiration by waterhyacinth may be important. The water is released to the atmosphere nutrient-free to reenter the hydrologic cycle, nutrients being held in the plant. The plant, in effect, is acting as a nutrient filter between the nutrient solution and the hydrologic cycle. Since the desired result is to return the water to the environment free of nutrients, this may be a beneficial effect.

The amounts of phosphorus absorbed per plant per day were essentially the same for the same solutions in both static water experiments (Table 1). The maximum was 3.1 mg/plant per day from 50% Hoagland's solution and the minimum was 1.1 mg/plant per day from the 10% Hoagland's solution. Since water was being absorbed at the same time as phosphorus, there was not a comparable decrease in phosphorus concentration in the solutions (Figures 2 to 5). In the single plant experiment (A) the concentration of phosphorus in milligrams per liter changed from 3.6 to 0.1, 3.0 to 0.9, 7.5 to 4.6, and 15.6 to 17.2 for sewage effluent and 10, 25, and 50% Hoagland's solution, respectively (tabular data not included). In the group plant experiment (B) the changes in phosphorus concentrations were 3.7 to 0.1, 3.1 to 1.1, 7.7 to 5.5, and 15.2 to 15.1 for sewage effluent, 10, 25, and 50% Hoagland's solution, respectively (Figures 3 to 6). Rohlich (13) reported phosphorus concentrations in sewage effluent from 1 to 13 mg/L. In these experiments, waterhyacinth plants rapidly decreased the phosphorus concentration when the initial concentration was 3.7 mg/L or less, were less effective when the initial concentration was 7.5 mg/L, and were not effective when the initial concentration was 15.6 mg/L.

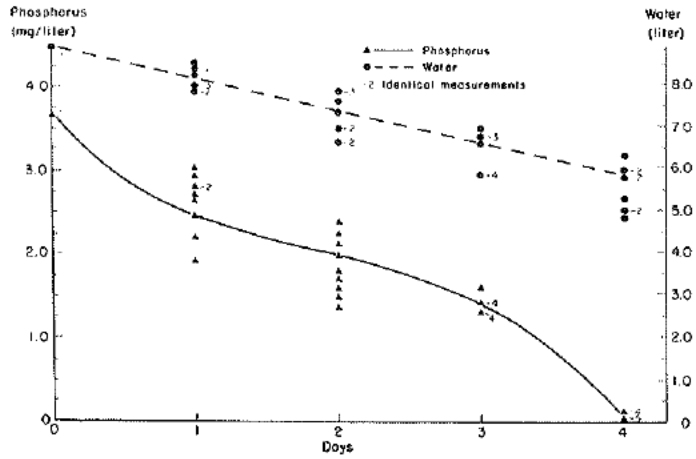

Figure 5. Effect of growing five waterhyacinth plants for 4 days in sewage effluent (Experiment B) on the amount of water remaining and its phosphorus concentration. Calculated regression equation for phosphorus concentration: $Y = 6.26 - 3.84X + 1.05X^2 - 0.12X^3$.

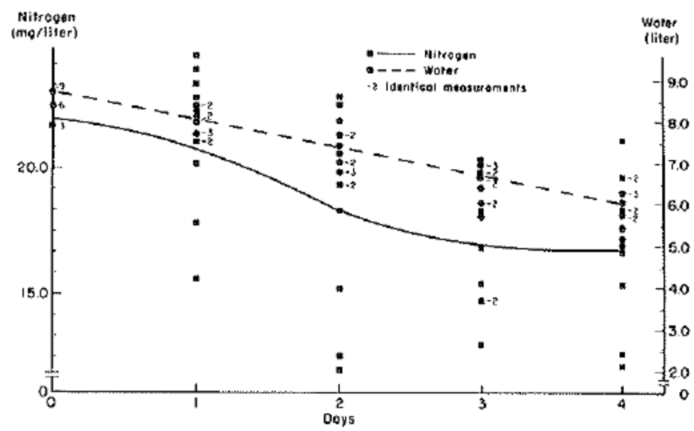

Figure 6. Effect of growing five waterhyacinth plants for 4 days in 10% Hoagland's solution (Experiment B) on the amount of water remaining and its nitrogen concentration. Calculated regression equation for nitrogen concentration: $Y = 20.03 + 4.67X - 2.66X^2 + 0.32X^3$.

In the group plant experiment (B) the phosphorus concentration of the solutions increased slightly after 1 day.

These increases were probably the result of an interaction between water loss by evapotranspiration and a slow initial phosphorus uptake since the plants had previously been growing in full-strength Hoagland's solution.

The patterns for nitrogen absorption were similar to those for phosphorus, and the amounts absorbed per plant per day were essentially the same for the same solutions in both static water experiments (Table 1 and Figures 6 to 9). The maximum absorption was 21.8 mg/plant per day

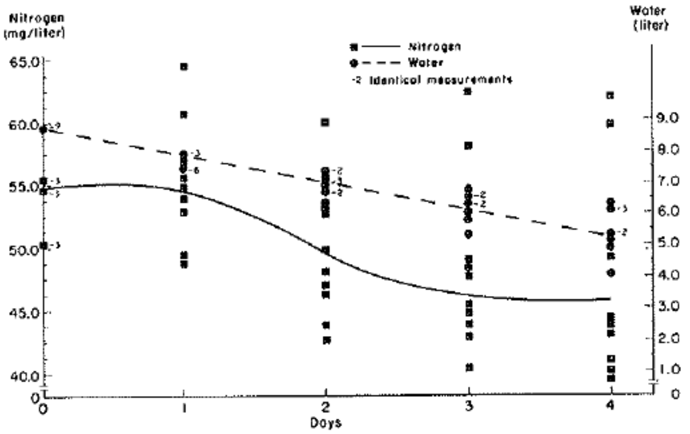

Figure 7. Effect of growing five waterhyacinth plants for 4 days in 25% Hoagland's solution (Experiment B) on the amount of water remaining and its nitrogen concentration. Calculated regression equation for nitrogen concentration: $Y = 43.72 - 16.51X - 6.82X^2 + 0.74X^3$.

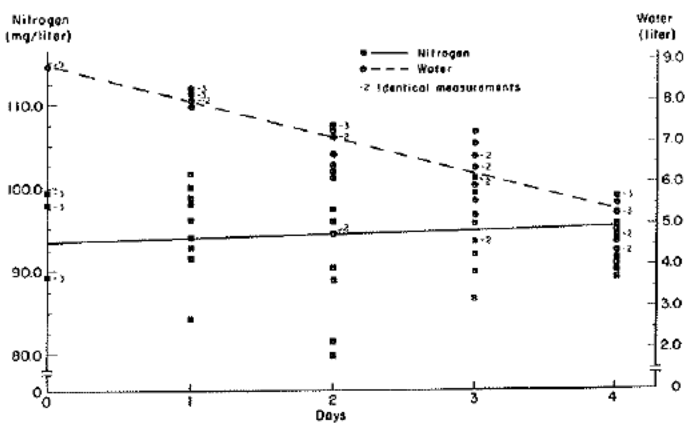

Figure 8. Effect of growing five waterhyacinth plants for 4 days in 50% Hoagland's solution (Experiment B) on the amount of water remaining and its nitrogen concentration. Calculated regression equation for nitrogen concentration: $Y = 93.96 + 0.19X$.

from 50% Hoagland's solution and the minimum was 4.7 mg/plant per day from 10% Hoagland's solution. There was no statistically significant differences in the amount absorbed from sewage effluent versus that from 10% Hoagland's solution in either of the two experiments. The ratio of nitrogen absorbed to phosphorus absorbed varied from about 5 to 1 to 6 to 1. Based on Boyd's data (2) the nitrogen to phosphorus ratio in waterhyacinth is about 6 to 1.

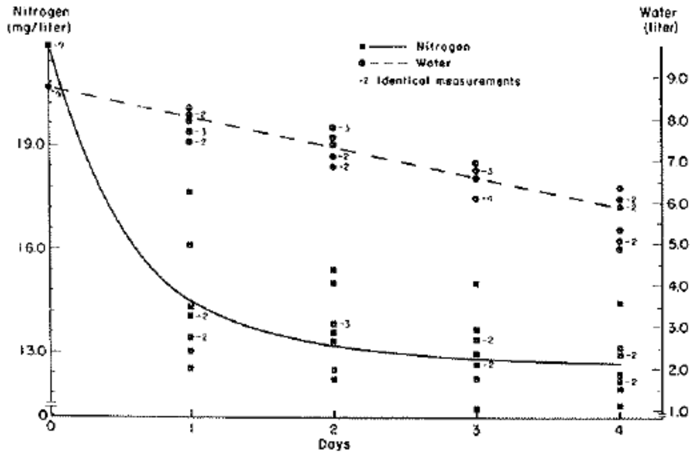

Figure 9. Effect of growing five waterhyacinth plants for 4 days in sewage effluent (Experiment B) on the amount of water remaining and its nitrogen concentration. Calculated regression equation for nitrogen concentration: $Y = 36.96 - 20.31X - 5.55X^2 - 0.50X^3$.

In the single plant experiment (A) the concentration of nitrogen in milligrams per liter in the solutions changed from 22 to 12, 23 to 15, 52 to 44, and 95 to 93 for the sewage effluent and 10, 25, and 50% Hoagland's solution, respectively (tabular data not included). In the group plant experiment (B) the changes in nitrogen concentrations were 22 to 12, 22 to 17, 54 to 48, and 96 to 97 mg/L for sewage effluent and 10, 25, and 50% Hoagland's solution, respectively (Figure 6 to 9). As was true for phosphorus, nitrogen absorption did not always reduce nitrogen concentration in the remaining solution. Waterhyacinth plants effectively decreased the nitrogen concentration in sewage effluent and in 10% Hoagland's solution but were ineffective in 50% Hoagland's solution. Rohlich (13) reported concentrations of 20 to 50 mg/L nitrogen in sewage effluent. Thus, waterhyacinth would be expected to effectively decrease nitrogen concentration for the lower concentrations but not the higher concentrations. Since the loss of water by evapotranspiration would tend to increase nitrogen concentration, then factors influencing the rate of evapotranspiration would be expected to influence the concentrations at which waterhyacinth would be effective in reducing nitrogen concentration.

In both static water experiments, readings with the dissolved solids meter indicated maximum absorption of dissolved solids from 50% Hoagland's solution (Table 1). In the single plant experiments (A) the calculated absorption based on reading by the dissolved solids meter did not show any difference between absorption from 25 and 10% Hoagland's solution while both nitrogen and phosphorus determinations did show a difference. The determinations with the dissolved solids meter more nearly paralleled those of nitrogen and phosphorus determinations in the group plant experiment (B) than in the single plant experiment (A). In general, the instrument seemed somewhat less sensitive to changes in nutrient status than found by direct chemical analyses. It did not always show a change when chemical analyses for nitrogen and phosphorus did, but it never indicated a significant decrease when neither the nitrogen nor the phosphorus had decreased.

Table 2. Effect of growing 30 waterhyacinth plants in a flowing system of 10, 25, and 50% Hoagland's solution on the nitrogen, phosphorus, and dissolved solids found in alternate 2.5-L fractions.[a]

Fraction no.	Phosphorus[b]			Nitrogen[b]			Dissolved solids[b]		
	10% H	25% H	50% H	10% H	25% H	50% H	10% H	25% H	50% H
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
1	2.9 a	7.7 a	15.4 b–e	25 a	59 a	88 ab	110 a	273 a	420 de
3	3.0 a	7.4 ab	15.2 b–e	25 a	56 a	88 ab	110 a	277 ab	420 de
5	2.8 a	7.3 a	14.9 cde	20 ab	56 a	93 a	103 a	253 b	425 d
7	2.5 ab	7.2 a	14.6 e	20 ab	52 b	92 a	77 b	230 c	420 de
9	2.1 bc	7.0 a	14.8 de	19 b	51 b	88 ab	77 b	227 cd	420 de
11	1.9 cd	6.7 bcd	14.9 cde	18 b	50 bc	91 ab	70 bc	220 cd	415 e
13	1.5 de	6.5 bcd	15.8 a–e	18 b	46 cde	87 ab	70 bc	217 cd	410 e
15	1.2 ef	6.5 bcd	16.1 a–d	19 b	47 cd	84 ab	67 bc	203 d	440 c
17	1.0 efg	6.5 bcd	16.5 ab	16 b	45 de	85 ab	67 bc	203 d	460 b
19	0.8 fg	6.4 bcd	17.1 a	17 b	42 de	84 ab	63 c	203 d	450 bc
21	0.6 g	6.2 cde	16.1 a–d	16 b	44 de	84 ab	70 bc	210 cd	460 b
23	0.6 g	5.9 def	16.5 ab	17 b	44 de	88 ab	70 bc	210 cd	420 de
25	0.5 g	5.7 ef	17.3 a	18 b	43 de	78 b	75 bc	210 cd	420 de
27	0.5 g	5.3 ef	17.0 a	18 b	43 de	85 ab	75 bc	210 cd	420 de
29		5.2 f	16.4 abc		43 de	84 ab		210 cd	420 de
31		5.3 ef	15.8 a–e		41 e	85 ab		210 cd	460 b
33			16.1 a–d			85 ab			480 a

[a]Elapsed time between alternate fractions varied slightly from run to run but averaged about 3 hr and 40 min.
[b]All values are averages from three experiments. The values 10, 25, and 50% H are fractions of full-strength Hoagland's solution. Values within a vertical column followed by the same letters are not significantly different at the 5% level.

Continuous flow experiment. The water loss per day per plant in the continuous flow experiment was not affected by the solution in which the plants were grown and averaged about 225 ml/plant per day (Table 1). Phosphorus absorption per plant per day was highest from 50% Hoagland's solution where it was 3.3 mg and lowest from 10% Hoagland's solution where it was 1.7 mg. These values are essentially the same as found in the static water experiments. Sewage effluent was not used in these studies because a uniform flow rate could not be maintained with such heterogeneous material. Phosphorus concentration decreased significantly by the seventh fraction in 10% Hoagland's solution, by the eleventh fraction in the 25% Hoagland's solution, and never in full strength Hoagland's solution (Table 2). The concentration of phosphorus in milligrams per liter changed from 2.9 to 0.5, 7.7 to 5.3, and 15.4 to 16.1 in the 10, 25, and 50% Hoagland's solution, respectively. The continuous flow experiment confirmed the effectiveness of waterhyacinth in decreasing the phosphorus concentration of moderately concentrated solutions but not of highly concentrated solutions.

Nitrogen absorption per plant per day was 9.9 mg from 10% Hoagland's solution, 18.4 mg from 25% Hoagland's solution, and 20.8 mg from 50% Hoagland's solution (Table 1). Nitrogen absorption was appreciably higher in the flowing water experiment than in the static water experiments from 10 and 25% Hoagland's solution but about the same from the 50% Hoagland's solution. Nitrogen concentration had significantly decreased by the ninth fraction from the 10% Hoagland's solution, by the seventh fraction of the 25% Hoagland's solution, and not at all for the 50% Hoagland's solution. Nitrogen concentration changed from 25 to 18, 59 to 41, and 88 to 85 mg/L in the 10, 25, and 50% Hoagland's solution, respectively. The continuous flow experiment thus gave similar results to the static water experiments, and nitrogen absorption paralleled phosphorus absorption.

The dissolved solids concentration was significantly lower in the 10% Hoagland's solution by the seventh fraction, in the 25% Hoagland's solution by the fifth fraction, and never in the 50% Hoagland's solution. As in the static water studies, the observed decreases in dissolved solids concentrations were similar to those determined for nitrogen and phosphorus concentrations.

Several workers have suggested the possible use of waterhyacinth for nutrient removal from waste waters (2, 14, 15, 17). These experiments confirm the validity of their suggestions for both static and flowing water systems but point out the lack of effectiveness of waterhyacinth in decreasing concentrations when the nutrient contents are quite high.

Penfound and Earle (12) have reported that 1 ha of waterhyacinth contains on the average about 1.62×10^6 plants. Lee (9) has reported that the annual domestic wastes per person is 0.908 kg of phosphorus and 3.178 kg of nitrogen. From these figures, it is apparent that 1 ha of waterhyacinth could absorb the nitrogen and phosphorus wastes of over 800 persons. These calculations assume maximum uptake by the plants and growth throughout the year. Neither of these situations could easily be achieved. The need to extend the growing season of waterhyacinth suggests additional potential benefits of their use. If enclosed under a plastic roof, a significant amount of the water lost by evapotranspiration could be condensed on the roof, collected, and used to further dilute the effluent water or could be recycled directly into the city water supply. The hot water produced by electric power plants and which is now itself a pollution problem could be used to further lengthen the growing season and to enhance evapotranspiration.

Acknowledgments

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