Oxygen Transport through Aquatic Macrophytes: The Role in Wastewater Treatment

K. R. Reddy,* E. M. D'Angelo and T. A. DeBusk

ABSTRACT

Laboratory experiments were conducted to determine the effectiveness of three floating and six emergent aquatic macrophytes in improving domestic wastewater quality, based on their capacities for O_2 transport into the effluent. Oxygen transport into the rooting zone of the plants created an oxidized microenvironment, thereby stimulating C and N transformations critical to wastewater treatment. Plants were cultured in flasks containing deoxygenated primary and secondary sewage effluent for an 8-d period. Oxygen transport by the plants was measured in terms of both O_2 consumed by the effluent (biological O_2 demand reduction—BOD_5) and increased effluent dissolved O_2. Two floating plants, pennywort (*Hydrocotyle umbellata* L.) and waterhyacinth [*Eichhornia crassipes* (Mart.) Solms], and the emergent plants pickerelweed (*Pontederia cordata* L.) and common arrowhead (*Sagittaria latifolia* L.), were superior in improving primary sewage effluent quality, by reducing BOD_5 up to 88%, NH_4-N up to 77%, and increasing dissolved O_2 up to 6.1 mg L^{-1}. Nitrification rates in pennywort- and water hyacinth-based water treatment systems were calculated to be in the range of 12 to 47 kg NH_4-N ha^{-1} d^{-1}. Oxygen transport through plants accounted for up to 90% of the total O_2 transported into the effluent. In separate batch experiments, the effectiveness of diffuse mechanical aeration (5 and 50 mL air min^{-1}) and of biological aeration (O_2 transport by selected plants including pennywort, waterhyacinth, pickerelweed, and common arrowhead) on the rate of contaminant removal from deoxygenated primary sewage effluent were compared for a 26-d period. Biological and mechanical aeration effected similar BOD_5 removal. First-order reaction rate constants for BOD_5 removal were from 0.0066 to 0.0079 h^{-1} and from 0.0041 to 0.0051 h^{-1} for biological and mechanical aeration, respectively. Rate constants for NH_4-N removal were from 0.0024 to 0.0107 h^{-1} for the plant treatments. Virtually complete BOD_5 removal occurred in biological and mechanical aeration treatments within 20 d. Complete nitrification of NH_4-N had occurred within 12 d after mechanical aeration was initiated, but subsequent N-loss by denitrification was inhibited. In the biological aeration treatments, negligible effluent (NO_3 + NO_2)-N levels were measured, but 65 to 100% NH_4-N loss occurred both by plant assimilation and by sequential nitrification-denitrification reactions.

AQUATIC PLANTS rooted in anaerobic sediments and anoxic waters transport O_2 through stems and leaves into their rooting zones. The mechanism of O_2 transport through aquatic plants into the rooting zone has been demonstrated by several researchers (Armstrong, 1964, 1967; Conway, 1937; Dacey, 1980; Grosse and Mevi-Schutz, 1987; Moorhead and Reddy, 1988; Teal and Kanwisher, 1966). Oxygen is used by plant roots for aerobic respiration. Indeed, tolerance to flooding is determined primarily by the capacities of plants to aerate their root systems (Armstrong, 1978). Moreover, rhizosphere oxidation detoxifies H_2S along with reduced forms of Fe and Mn (Armstrong, 1971; Gambrell and Patrick, 1978; Ponnamperuma, 1965) and activates biogeochemical processes including oxidation of soluble organic compounds and nitrification of NH_4-N (Good and Patrick, 1987; Reddy et al., 1989). Thus, rhizosphere oxidation has important implications in wastewater treatment.

In the past decade, use of the aquatic macrophytes cultured in shallow ponds and artificial wetlands for wastewater treatment has proved economically feasible for small communities (Crites and Mingee, 1987; Duffer, 1982; Reed et al., 1988). To improve wastewater treatment efficiency and to reduce production of odors and mosquitoes (*Culex* spp. and *Anopheles* spp.), mechanical aeration was suggested for ponds containing floating aquatic macrophytes (Reed et al., 1988), since O_2 transport through the plants was thought to be insufficient to support maximum root and microbial respiration. However, a recent study (DeBusk et al., 1989) has shown no consistent water quality improvement in waterhyacinth ponds having mechanical aeration. Weber and Tchobanoglous (1986) and DeBusk et al. (1989) also did not recommend mechanical aeration, because of its energy requirements.

The success of using aquatic plants for secondary treatment of primary sewage effluent is dependent on the capacity of plants to transport O_2 into the root zone, with subsequent utilization of the excess O_2 during microbial respiration. Selection of suitable aquatic macrophytes plays a critical role in optimizing these systems for maximum contaminant removal.

Numerous studies have evaluated the potential nutrient removal via plant assimilation for wastewater treatment (Reddy, 1983, 1984; Reddy and DeBusk, 1985), but the role of O_2 transport by several aquatic macrophytes commonly used for wastewater treatment has yet to be studied intensively. To evaluate this mechanism, laboratory experiments were conducted with the following objectives: (i) to determine the O_2 transport capacity of aquatic macrophytes as determined by wastewater BOD_5 (biological O_2 demand) reduction, and (ii) to compare the efficiency of biological aeration (O_2 transport through plants) with mechanical diffuse aeration in reducing BOD_5 of primary sewage effluent.

MATERIALS AND METHODS

Aquatic plants were obtained from the St. Johns River marsh and were cultured in 10% modified Hoagland nutrient solutions until used in the experiments (Reddy and DeBusk, 1985). A total of nine plant treatments (three floating and six emergent macrophytes) were evaluated (see Table 1 for list of plants). Many of these plants are currently used in aquatic plant-based water treatment systems (Tchobanoglous, 1987; Wolverton, 1987). Primary sewage effluent was obtained from the Reedy Creek Improvement District sewage treatment facility located at Lake Buena Vista, FL. Statistical significance of the data was evaluated using the general linear model (SAS Inst., 1985).

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Experiment 1

The apparatus used in the first experiment (Objective 1) consisted of a 500 mL widemouth flask wrapped in aluminum foil and filled with primary sewage effluent. After plants were introduced into the flasks, the effluent was purged with N_2 for 25 min to reduce dissolved O_2 (DO) to <0.3 mg L^{-1}. Oxygen was determined using a Yellow Springs Instrument (Yellow Springs, OH) dissolved oxygen electrode. There were three replications for each of the following treatments:

PB = Plant with Barrier.

A plant was placed in a split-rubber stopper having a center hole approximately 2 cm in diam. The excess space surrounding the plant was plugged with glazing seal. A flask containing deoxygenated primary sewage effluent was stoppered using the split-rubber stopper containing the plant. This treatment allowed evaluation of O_2 transport through the plant only.

PNB = Plant without Barrier.

A plant supported by wire was placed into a flask containing deoxygenated primary sewage effluent. This treatment allowed evaluation of O_2 transport through the plant along with concurrent O_2 diffusion into the water column surrounding the plant.

B = Flask with No Plant but with a Barrier.

A rubber stopper was placed on a flask containing deoxygenated primary sewage effluent to prevent subsequent O_2 diffusion. This treatment allowed evaluation of the role of anaerobic microorganisms in reducing BOD_5 of the primary sewage effluent.

NB = Flask with No Plant and No Barrier.

The flask containing deoxygenated primary sewage effluent was left exposed to air. This treatment allowed evaluation of the role of O_2 diffusion from the atmosphere in reducing the BOD_5 of the effluent.

All flasks were placed under lights (250 μE cm^{-2} s^{-1}) with a 12-h light/12-h dark cycle at laboratory temperature (25 °C) for 8 d.

Experiment 2

A second experiment using anatomically similar plants of the same species as Experiment 1 (listed in Table 1) was conducted using primary sewage effluent that had been diluted to approximate the BOD_5 of secondary sewage effluent. The same treatments as described above were evaluated using this diluted effluent, with three replications for each treatment. To avoid N-limiting conditions for plant growth, the diluted effluent was spiked with NH_4-N to maintain the N levels of undiluted effluent. The hypothesis tested was that O_2 transported from the foliage to the rooting zone of the plants would be adequate to support both heterotrophic microbial respiration and nitrification of NH_4-N.

At the end of Experiments 1 and 2, effluent was mixed with a magnetic stirrer, and analyzed for DO, BOD_5 total kjeldahl-N (TKN), NH_4-N, and (NO_3 + NO_2)-N using standard methods (APHA, 1985). Plant root and shoot fresh and dry weights were determined. Oxygen-transport rates were calculated using the following equation:

$$O_2 \text{ Transport} = BOD_5 \text{ (Initial} - \text{Final)} + \text{DO (Final} - \text{Initial)}$$

Experiment 3

A third experiment (Objective 2) was conducted to compare the efficiency of biological aeration with mechanical diffuse aeration. Biological aeration was provided by the aquatic plants, waterhyacinth, pennywort, pickerelweed, and common arrowhead, chosen because of their superior O_2 transport rates measured in the previous two experiments. Two mechanical aeration levels (5 and 50 mL min^{-1}) were evaluated by bubbling air from aquarium pumps through porous aquarium stones into primary sewage effluent throughout the duration of the experiment. Air-flow rates were continuously monitored using air-flow meters. The effects of aeration by atmospheric diffusion were also evaluated. The experimental apparatus consisted of 1200 mL Plexiglas cylinders (19 cm long and 9 cm diam.), each furnished with six rubber septa and a magnetic stirring bar. Primary sewage effluent and plant roots were introduced into the cylinder and bubbled with N_2 gas for 40 min to remove DO to <0.3 mg L^{-1}. There were three replications of each treatment. The split-rubber stoppers used to support the plant were sealed with glazing seal. The split-rubber stopper barrier ensured that O_2 transport occurred only through the aerial portion of the plant into the rooting zone. The technique was similar to that described by Moorhead and Reddy (1988).

At each sampling period, each cylinder containing effluent was stirred with a magnetic stirrer for 5 min. A 50-mL aliquot was removed with a large syringe through a rubber septum at 0, 24, 72, 120, 168, 288, 456, and 624 h. Samples were analyzed for BOD_5, TKN, NH_4-N, and (NO_3 + NO_2)-N using standard methods (APHA, 1985). Deoxygenated distilled water was added to replace the volumes of water lost by evaporation, transpiration and sample removal. At the end of the experiment, plant fresh and dry weights were determined.

RESULTS

Oxygen Transport through Plants (Experiments 1 and 2)

Increase in effluent DO (Table 1) at the end of the 8-d retention period did not represent the total amount of O_2 transported by the plant, because a significant amount of the O_2 transported was subsequently consumed during microbial respiration. Net increase in primary sewage effluent DO (high O_2-demand effluent) was in the range of 1.1 to 6.1 mg L^{-1} for floating plants, and 1.0 to 5.4 mg L^{-1} for emergent plants. The net increase in secondary effluent DO (low O_2-demand

Table 1. Dissolved O_2 concentrations of the water column at the end of an 8-d incubation period. Each value represents the mean of three replicates.

	Primary sewage effluent		Secondary sewage effluent	
Macrophyte	Barrier	No barrier	Barrier	No barrier
	mg L^{-1}			
Floating aquatic plants				
Pennywort	5.3a*	6.1a	6.1a	7.4a
Waterhyacinth	3.4b	4.9b	6.0a	6.3ab
Waterlettuce	1.1gh	2.0d	1.1de	2.5de
Emergent aquatic plants				
Pontederia cordata	3.2bc	5.4b	2.3b	5.6b
Common cattail *(Typha latifolia)*	1.7efg	1.4de	1.2cd	1.4ef
Common arrowhead	2.0def	1.7d	2.0b	2.2de
Canna flaccida	2.3cde	3.1c	1.8bc	4.0c
Scirpus pungens	1.2fgh	1.0e	0.5e	0.8ef
Scirpus validus	2.8bcd	3.1c	2.1b	3.1cd
No plants	0.8h	0.8e	0.8de	1.4ef

* Means in the same column with the same letter suffix are not significantly different at P = 0.05.

Table 2. Percent BOD_5 removal from the water column at the end of an 8-d incubation period. Each value is the mean of three replicates.

Macrophyte	Primary sewage effluent			Secondary sewage effluent		
	Intitial	Barrier	No barrier	Intitial	Barrier	No barrier
	mg L^{-1}	% BOD_5 removal		mg L^{-1}	% BOD_5 removal	
Floating aquatic plants						
Pennywort	178.8	87.0a*	88.3a	47.2	88.7a	74.9b
Waterhyacinth	112.2	73.9ab	79.8bc	45.6	89.9a	91.4a
Waterlettuce	141.1	66.9bc	72.7cd	47.6	67.1ab	77.7b
Emergent aquatic plants						
Pontederia cordata	178.8	84.1a	84.9ab	47.2	83.3a	83.4ab
Common cattail	137.5	37.9ef	70.4d	48.7	44.2b	24.2d
Common arrowhead	127.4	78.9ab	83.8ab	32.5	64.1ab	71.5b
Canna flaccida	170.5	56.0cd	60.3ef	56.9	77.1a	78.6ab
Scirpus pungens	137.5	30.0f	54.3f	48.7	2.4c	46.2c
Scirpus validus	170.5	50.8de	65.5de	56.9	69.9ab	83.3ab
No plants	142.2	−4.2g	55.9f	42.1	5.23c	58.5c

* Means in the same column with the same letter suffix are not significantly different at P = 0.05.

effluent) was in the range of 1.1 to 7.4 mg L^{-1} for floating plants and 0.5 to 5.6 mg L^{-1} for emergent plants. The effluent in flasks containing pennywort contained more DO than in flasks containing other floating or emergent plants. Among emergent aquatic plants, pickerelweed ranked highest in terms of increased effluent DO levels. The effluent DO with no plants present was 0.8 mg L^{-1} for primary sewage effluent and 1.4 mg L^{-1} for secondary effluent.

The initial primary sewage effluent BOD_5 used in the experiments ranged from 112 to 179 mg L^{-1}, whereas the initial secondary sewage effluent BOD_5 was in the range 42 to 57 mg L^{-1} (Table 2). At the end of an 8-d retention period, the primary sewage effluent BOD_5 decreased to less than 27 mg L^{-1} when treated with pennywort, waterhyacinth, pickerelweed, and arrowhead. The BOD_5 of secondary effluent was reduced below 10 mg L^{-1} by the above species and by *Scirpus validus*.

The BOD_5 is a "measurement of the total O_2 required for the oxidation of organic C and reduced N compounds; along with reduced forms of sulfides and ferrous iron" of the effluent (APHA,1 985). Therefore, O_2 consumption (BOD_5 reduction) plus DO accumulation in the effluent during an 8-d retention period was used as an indicator of total O_2 transport into the effluent by the plants (Tables 3 and 4). Among floating aquatic plants pennywort ranked highest, with an O_2 transport capacity of 13 mg O_2 d^{-1}. Among emergent plants pickerelweed ranked highest, at 12.5 mg O_2 d^{-1}. Moorhead and Reddy (1988) found a correlation between dry root mass and O_2 transport rates into the root zone of aquatic plants, therefore, O_2 transport rates were also expressed based on root mass. On this

Table 3. Oxygen transport into primary sewage effluent by selected aquatic macrophytes (Experiment 1). Each value represents the mean of three replications.

Macrophyte		Biomass			Shoot/Root ratio	Oxygen transport	
		Root	Shoot	Total			
		g (dry wt) $plant^{-1}$				mg O_2 d^{-1}	mg O_2 g^{-1} root d^{-1}
Floating aquatic macrophytes							
Pennywort	B†	0.12	0.29	0.41	2.41	12.9a*	111.7a
	NB	0.12	0.43	0.54	3.58	13.2a	115.7a
Wateryacinth	B	0.13	0.49	0.62	3.77	6.8cd	54.5b
	NB	0.13	0.66	0.79	5.08	7.5bc	57.3b
Waterlettuce	B	0.20	1.27	1.48	6.35	7.8bc	38.4bc
	NB	0.20	1.29	1.49	6.45	8.4bc	49.7b
Emergent aquatic macrophytes							
Pontederia cordata	B	0.86	3.61	4.47	4.20	12.5a	18.8cd
	NB	0.35	3.68	4.03	10.51	12.5a	36.6bc
Common cattail	B	1.32	2.31	3.63	1.75	4.4e	3.8d
	NB	1.21	2.65	3.86	2.19	8.0bc	4.7d
Common arrowhead	B	0.44	1.08	1.52	2.45	8.3bc	19.4cd
	NB	0.47	1.21	1.68	2.57	8.8bc	21.2cd
Canna flaccida	B	0.60	2.34	2.94	3.90	7.9bc	25.8c
	NB	0.38	2.66	3.04	7.00	8.5bc	13.8cd
Scirpus pungens	B	0.81	1.15	1.96	1.42	3.4e	4.4d
	NB	0.47	0.89	1.36	1.89	6.1cd	13.4cd
Scirpus validus	B	0.30	2.56	2.86	8.53	7.3bc	24.3c
	NB	0.33	3.27	3.60	9.91	9.2b	29.6c

* Means in the same column with the same letter suffix are not significant at P = 0.05.
† B = barrier; NB = no barrier.

Table 4. Oxygen transport into secondary sewage effluent by selected aquatic macrophytes (Experiment 2). Each value represents the mean of three replications.

Macrophyte		Biomass			Shoot/Root ratio	Oxygen transport	
		Root	Shoot	Total			
		g (dry wt) plant^{-1}				mg O_2 d^{-1}	mg O_2 g^{-1} root d^{-1}
Floating aquatic macrophytes							
Pennywort	B†	0.15	0.43	0.58	2.87	3.9a*	25.7a
	NB	0.11	0.34	0.45	3.09	3.4ab	29.8a
Wateryacinth	B	0.19	0.68	0.87	3.58	3.7a	19.8ab
	NB	0.19	0.75	0.94	4.95	3.9a	20.7ab
Waterlettuce	B	0.21	1.32	1.53	6.29	2.8bc	13.2bc
	NB	0.16	1.46	1.62	9.13	3.2ab	20.0ab
Emergent aquatic macrophytes							
Pontederia cordata	B	0.44	4.03	4.47	9.16	3.6a	8.3bcd
	NB	0.32	3.22	3.54	10.06	3.6a	11.1bcd
Common cattail	B	0.92	3.58	4.50	4.89	1.9c	2.1d
	NB	0.63	3.49	4.12	6.54	1.1d	1.8d
Common arrowhead	B	0.42	0.96	1.38	3.29	1.9c	4.5d
	NB	0.25	0.87	1.12	4.48	2.1c	8.3bcd
Canna flaccida	B	0.53	2.61	3.14	4.92	3.8a	7.2cd
	NB	0.46	2.14	2.60	4.65	4.0a	8.7bcd
Scirpus pungens	B	0.36	0.89	1.25	2.47	−0.8e	N/A
	NB	0.23	0.61	0.84	2.65	1.9c	8.2bcd
Scirpus validus	B	0.25	2.57	2.82	10.28	3.5ab	13.8bc
	NB	0.24	3.13	3.36	13.04	4.1a	16.8b

* Means in the same column with the same letter suffix are not significant at $P = 0.05$.
† B = barrier; NB = no barrier.

basis, pennywort had the highest O_2 transport capacity of 116 mg O_2 g^{-1} root d^{-1} (Table 3). Oxygen transport by waterhyacinth was 57 mg O_2 g^{-1} root d^{-1}; whereas, O_2 transport by emergent macrophytes ranged from 3.8 to 24.4 mg O_2 g^{-1} root d^{-1}. Oxygen transport by plants decreased with decreasing effluent O_2 demand. In this study, it was found that high O_2 demand effluent created conditions favorable for increased mass flow of air through plant internal air spaces into the effluent. The mass flow is driven by the increased consumption of O_2 by the microorganisms, and the solubilization of respiratory CO_2 into the effluent (Raskin and Kende, 1985). Plants cultured in secondary effluent (low O_2-demand effluent) exhibited an O_2 transport capacity of 13 to 26 mg O_2 g^{-1} root d^{-1} for floating aquatic plants, and of 2 to 14 mg O_2 g^{-1} root d^{-1} for emergent aquatic plants.

Oxygen transport directly through the plants accounted for greater than 90% of the total O_2 transported into the effluent. Less than 10% of the total effluent O_2 diffused directly from the atmosphere.

Reduction in effluent NH_4-N and TKN as influenced by O_2 transport through the plants is shown in Tables 5 and 6. Initial NH_4-N of the primary sewage effluent was between 17 to 40 mg L^{-1}, whereas the secondary sewage effluent was spiked with NH_4-N to obtain the same range. Effluent (NO_3 + NO_2)-N was low for all treatments.

Biological verses Mechanical Aeration (Experiment 3)

Aquatic plants effected similar levels of wastewater BOD_5 reduction as mechanical aeration (Fig. 1). Pen-

Table 5. Percent ammonium-N removal from the water column at the end of an 8-d incubation period. Each value represents the mean of three replicates.

Macrophyte	Primary sewage effluent			Secondary sewage effluent		
	Intitial	Barrier	No barrier	Intitial	Barrier	No barrier
	mg L^{-1}	% NH_4-N removal		mg L^{-1}	% NH_4-N removal	
Floating aquatic plants						
Pennywort	17.4	35.9cd*	41.0bcd	26.5	14.5def	48.9a
Wateryacinth	18.5	61.8ab	69.9a	22.9	56.6a	38.2abc
Waterlettuce	32.2	26.8de	32.1cde	37.3	49.4ab	45.5ab
Emergent aquatic plants						
Pontederia cordata	32.3	53.9bc	49.9abc	27.3	34.9bc	32.4bcde
Common cattail	40.5	25.8de	31.8cde	40.0	22.8cde	28.2cde
Common arrowhead	22.1	77.0a	65.4ab	30.0	27.8cde	41.6abc
Canna flaccida	28.6	36.6cd	32.0cde	32.1	30.8cd	36.2abcd
Scirpus pungens	40.5	6.1fg	14.7cde	40.0	13.3ef	20.1e
Scirpus validus	28.6	9.8ef	−20.9f	32.1	21.0cdef	17.3e
No plants	18.4	11.0g	12.8c	23.7	4.9f	22.1de

* Means in the same column with the same letter suffix are not significantly different at P = 0.05.

Table 6. Percent total kjeldahl-N removal from the water column at the end of an 8-day incubation period. Each value represents the mean of 3 replicates.

Macrophyte	Primary sewage effluent			Secondary sewage effluent		
	Intitial	Barrier	No barrier	Intitial	Barrier	No barrier
	mg L^{-1}	% TKN removal		mg L^{-1}	% TKN removal	
Floating aquatic plants						
Pennywort	24.3	38.5cd*	42.9bc	27.8	4.2f	24.8de
Wateryacinth	27.8	58.8ab	66.6a	33.9	59.1a	47.7a
Waterlettuce	40.0	26.0de	22.1de	40.9	44.6b	51.7a
Emergent aquatic plants						
Pontederia cordata	35.7	43.3bc	37.9cd	38.8	46.1ab	46.0ab
Common cattail	52.5	29.6cde	32.3cde	45.8	21.1de	27.4cde
Common arrowhead	30.0	67.9a	61.3ab	35.4	28.4cd	33.8bcd
Canna flaccida	39.5	37.6cd	37.6cd	39.9	35.2bc	38.9abc
Scirpus pungens	52.5	9.6f	17.0e	45.8	11.0ef	14.8ef
Scirpus validus	39.5	14.3ef	30.8cde	39.9	27.0cd	21.5de
No plants	30.5	2.3f	14.2e	30.8	−1.3f	8.1f

* Means in the same column with the same letter suffix are not significantly different at P = 0.05.

nywort, waterhyacinth, and pickerelweed were the species most efficient in reducing BOD_5 of the effluent (70% reduction during the first 5 d). During the same period, mechanical aeration also reduced BOD_5 by about 70%. After approximately 10 d, 90% of the BOD_5 was reduced in all treatments and there was no significant difference between biological aeration and mechanical aeration. The first-order BOD_5 removal rate constants were from 0.0066 to 0.0079 h^{-1} (r^2 = 0.916–0.981) and from 0.0041 to 0.0051 h^{-1} (r^2 = 0.887–0.912) for biological and mechanical aeration, respectively. The BOD_5 removal rate constant was 0.0023 h^{-1} for atmospheric diffusion into the primary sewage effluent.

Complete conversion of primary effluent NH_4-N to (NO_3 + NO_2)-N (nitrification) had occurred by the end of 624 h for the mechanical aeration treatments (5 and 50 mL min^{-1}) (Fig. 2a). Between 65 and 100% of the effluent NH_4-N was also lost from the plant treatments (Fig. 2b), but no effluent (NO_3 + NO_2)-N was measured (Fig. 3). The first-order NH_4-N removal rate constants were from 0.0024 to 0.0107 h^{-1} (r^2 = 0.953–0.982) for biological aeration. Sigmoidal NH_4-

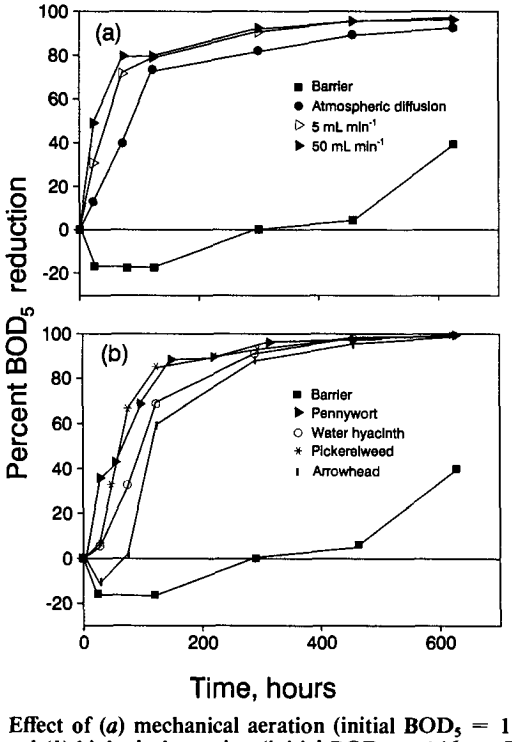

Fig. 1. Effect of (*a*) mechanical aeration (initial BOD_5 = 181 mg L^{-1}) and (*b*) biological aeration (initial BOD_5 = 146 mg L^{-1}) on the BOD_5 reduction of primary sewage effluent. Barrier = the effluent isolated from the atmosphere. Mechanical aeration = bubbling air into the effluent at pre-determined flow rates. Atmospheric diffusion = open flasks allowing atmospheric air diffusion into the effluent. Biological aeration = O_2 transport only through the plants into the effluent. Each value represents the mean of three replicates.

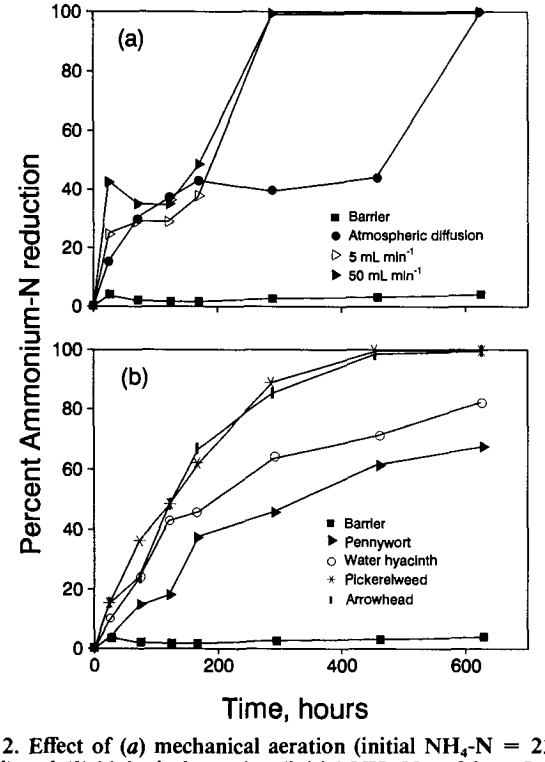

Fig. 2. Effect of (*a*) mechanical aeration (initial NH_4-N = 23 mg L^{-1}) and (*b*) biological aeration (initial NH_4-N = 26 mg L^{-1}) on the BOD_5 reduction of primary sewage effluent. Barrier = the effluent isolated from the atmosphere. Mechanical aeration = bubbling air into the effluent at pre-determined flow rates. Atmospheric diffusion = open flasks allowing atmospheric air diffusion into the effluent. Biological aeration = O_2 transport only through the plants into the effluent. Each value represents the mean of three replicates.

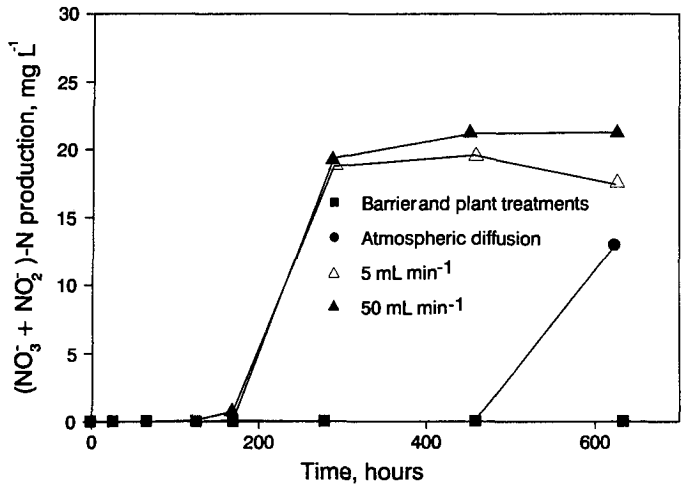

Fig. 3. Effect of mechanical and biological aeration on (NO_3 + NO_2)-N production in primary sewage effluent. Barrier = the effluent isolated from the atmosphere. Mechanical aeration = bubbling air into the effluent at pre-determined flow rates. Atmospheric diffusion = open flasks allowing atmospheric air diffusion into the effluent. Biological aeration = O_2 transport only through the plants into the effluent. Each value represents the mean of three replicates.

N removal was observed for the treatments with mechanical aeration. The initial decrease in NH_4-N was probably due to NH_3 volatilization, with the subsequent NH_4-N loss due to nitrification-denitrification reactions.

DISCUSSION

Previous studies have shown that certain aquatic plants can improve the quality of wastewater effluent by means of nutrient assimilation and solids filtration mechanisms. However, these processes cannot account entirely for the high pollutant-removal rates observed at many aquatic plant-based wastewater treatment systems (Brix, 1987; Gersberg et al., 1986; Nichols, 1983; Stephenson et al., 1980). The major mechanisms for pollutant removal are microbially mediated nutrient transformations including organic N and C compound oxidation (Reddy, 1983, 1984) referenced in this study to BOD_5 reduction, organic-N mineralization, and NH_4-N loss. Plants transport O_2 from foliage to roots (Armstrong, 1964), resulting in an oxidized microenvironment in the rooting zone. This may stimulate both the decomposition of organic matter and the growth of nitrifying bacteria. The NO_3-N formed during nitrification can then diffuse to anoxic regions, where it will be converted to N_2 gas and lost from the system. The floating macrophytes pennywort, waterhyacinth, and waterlettuce, (*Pistia stratiotes* L.), and the emergent macrophytes pickerelweed and common arrowhead, were superior in increasing effluent DO and removal of organic-N and NH_4-N, and BOD_5. In studies by Moorhead and Reddy (1988), highest O_2 transport capacities into distilled water were also found in pennywort, pickerelweed, and waterhyacinth.

The stoichiometric nitrification equation requires 4.3 mg O_2 per mg NH_4-N nitrified (Barnes and Bliss, 1983). The O_2 transport capacities of pennywort and hyacinth are 27.5 and 10.1 mg O_2 g^{-1} plant (dry wt.) d^{-1}, respectively (Table 3). Operational plant densities of pennywort and waterhyacinth in aquatic plant-based water-treatment systems are 250 to 650 and 500 to 2000 g plant (dry wt.) m^{-2}, respectively (Reddy and DeBusk, 1985). If O_2 consumption is due entirely to nitrification, from 16 to 42 and from 12 to 47 kg NH_4-N ha^{-1} d^{-1} would be nitrified in pennywort- and hyacinth-based water treatment systems, respectively. Hauser (1984) measured removal rates of about 17 kg NH_4-N ha^{-1} d^{-1} at 3-d retention periods, whereas Weber and Tchobanoglous (1985) measured removal rates of about 35 kg NH_4-N ha^{-1} d^{-1} for 2-d retention periods in large-scale waterhyacinth-based water treatment systems. Variability in N removal rates among researchers arises from differences in design criteria and substrate of the aquatic system (Weber and Tchobanoglous, 1985), and other factors that may affect the growth of microorganisms. In Experiment 3, which compared the effects of plant aeration and mechanical aeration on N removal, the role of O_2 transport on nitrification-denitrification was illustrated. At both aeration levels (5 and 50 mL min^{-1}), complete nitrification of NH_4-N had occurred within 12 d, with (NO_3 + NO_2)-N remaining in the effluent for the duration of the experiment. For the plant treatments, similar effluent NH_4-N losses were measured, but negligible (NO_3 + NO_2)-N was measured. Both denitrification of NO_3-N to N_2 in effluent anaerobic zones, and plant assimilation of effluent NH_4-N and NO_3-N, accounted for N losses in these plant systems. In comparing the performance of flasks with plants to those without plants, it should be noted that the plant roots provide an ideal site for microbial attachment. Hence, between-treatment differences in contaminant-removal rates may be related to bacterial populations present in the flask as well as to plant O_2 transport rates. Reddy et al. (1989) have shown direct evidence of significant amounts of $^{15}NH_4$-N loss from the rooting zone of rice (*Oryza sativa* L.), *Pontederia cordata*, and *Juncus effusus*, as a result of nitrification-denitrification and ultimate transport of N_2 through the plant into the atmosphere above the floodwater.

Distinct differences in the abilities of various aquatic plants to oxidize the rooting zone and it surrounding medium are attributed to many factors. Armstrong (1971) found that differences in root respiratory activity accounted for differences in radial O_2 losses (ROL). High root respiration rates reduce the O_2 available for diffusion to the anoxic rooting medium. Respiratory activity may be reduced by the development of cortical lacunae in some roots grown under flooded conditions. The lacunar system and aerenchyma tissue also increase O_2 transport, by forming continuous networks of enlarged intercellular spaces connecting the rooting zone to the atmosphere (Conway, 1937; Hutchinson, 1975; Sculthorpe, 1967; van Raalte, 1940; Williams and Barber, 1961). Some plants have root walls more permeable to O_2 diffusion (Armstrong, 1971). Formation of waxy or fatty substances in the cell walls of mature roots may result in reduced root-wall porosity and permeability to O_2, thus lowering O_2 transport rates (Armstrong, 1967). Increased root length may also reduce ROL from the

roots, due to the increased distance from the O_2 source (the atmosphere) to the apical root section (Luxmoore and Stolzy, 1972). In addition to O_2, root exudation of carbohydrates, enzymes, and other compounds into the rhizosphere influences both plant adaptation to anoxia (Hook, 1984), and microbial reactions important to wastewater treatment (Good and Patrick, 1987). For these reasons, O_2 transport capacity as well as plant assimilation should be considered as important design criteria for aquatic plant-based wastewater-treatment systems.

REFERENCES

American Public Health Association, 1985. Standard methods for the examination of water and wastewater. 16th ed. APHA, Washington, DC.

Armstrong, W. 1964. Oxygen diffusion from the roots of some British bog plants. Nature (London) 204:801–802.

Armstrong, W. 1967. The use of polarography in the assay of oxygen diffusing from roots in anaerobic media. Physiol. Plant. 20:540–553.

Armstrong, W. 1971. Radial oxygen loses from intact rice roots as affected by distance from the apex, respiration and waterlogging. Physiol. Plant. 25:192–197.

Armstrong, W. 1978. Root aeration in wetland conditions. p. 269–297. *In* D.D. Hook and R.M.M. Crawford (ed.) Plant life in anaerobic environments. Ann Arbor Science, Ann Arbor, MI.

Barnes, D., and P.J Bliss. 1983. Theory of nitrification. p. 29–47. *In* Biological control of nitrogen in wastewater treatment. E. and F.N. Spon, New York.

Brix, H. 1987. Treatment of wastewater in the rhizosphere of wetland plants—the root-zone method. Water Sci. Technol. 19:107–118.

Conway, V.M. 1937. Studies in the autecology of *Cladium mariscus* R. Br. III. The aeration of the subterranean parts of the plant. New Phytol. 36:64–96.

Crites, R.W., and T.J. Mingee. 1987. Economics of aquatic wastewater treatment systems. p. 879–888. *In* K.R. Reddy and W.H. Smith (ed.) Aquatic plants for water treatment and resource recovery. Magnolia Publ., Orlando, FL.

Dacey, J.W.H. 1980. Internal winds in water lilies: An adaptation for life in anaerobic sediments. Science (Washington, DC) 210:1017–1019.

DeBusk, T.A., K.R. Reddy, and K.S. Clough. 1989. Effectiveness of mechanical aeration in floating aquatic macrophyte-based wastewater treatment systems. J. Environ. Qual. 18:349–354.

Duffer, W.R. 1982. Assessment of aquaculture for reclamation of wastewater. p. 349–367. *In* E.J. Middlebrooks (ed.) Water reuse. Ann Arbor Science, Ann Arbor, MI.

Gambrell, R.P., and W.H. Patrick, Jr. 1978. Chemical and microbiological properties of anaerobic soils and sediments. p. 375–423. *In* D.D. Hook and R.M.M. Crawford (ed.) Plant life in anaerobic environments. Ann Arbor, MI.

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

Good, B.S., and W.H. Patrick, Jr. 1987. Root-water-sediment interface processes. p. 359–371. *In* K.R. Reddy and W.H. Smith (ed.) Aquatic plants for water treatment and resource recovery. Magnolia Publ., Orlando, FL.

Grosse, W., and J. Mevi-Schutz. 1987. A beneficial gas transport system in *Nymphoides peltata*. Am. J. Bot. 74:947–952.

Hauser, J.H. 1984. Use of water hyacinth aquatic treatment systems for ammonia control and effluent polishing. Water Pollut. Control Fed. 56:219–225.

Hook, D.D. 1984. Adaptations to flooding with freshwater. p. 265–294. *In* T.T. Kozlowski and A.J. Ricker (ed.) Flooding and plant growth, Academic Press, New York.

Hutchinson, G.E. 1975. Biological characteristics of the Tracheophytes of inland waters. p. 134–263. *In* A treatise on limnology. Vol. 3. Wiley-Interscience, New York.

Luxmoore, R.J., and L.H. Stolzy. 1972. Oxygen diffusion in the soil-plant system. VI. A synopsis with commentary. Agron. J. 64:725–729.

Moorhead, K.K., and K.R. Reddy. 1988. Oxygen transport through selected aquatic macrophytes. J. Environ. Qual. 17:138–142.

Nichols, S. 1983. Capacity of natural wetlands to remove nutrients from wastewater. J. Water Pollut. Control Fed. 55:495–505.

Ponnamperuma, F.N. 1965. Dynamic aspects of flooded soils and the nutrition of the rice plant. p. 295–328. *In* The mineral nutrition of the rice plant. John Hopkins Press, Baltimore, MD.

Raskin, I., and H. Kende. 1985. Mechanism of aeration in rice. Science (Washington, DC) 228:327–329.

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. 1984. Nutrient transformations in aquatic macrophyte filters used for water purification. p. 660–678. *In* Future of water reuse. Vol. 2. Proc. of Water Reuse Symp. III, San Diego, CA. 26–31 August. AWWA Research Foundation, Denver, CO.

Reddy, K.R., and W.F. DeBusk. 1985. Nutrient removal potential of selected aquatic macrophytes. J. Environ. Qual. 14:459–462.

Reddy, K.R., W.H. Patrick, Jr., and C.W. Lindau. 1989. Nitrification-denitrification at the plant-root-sediment interface in wetlands. Limnol. Oceanogr. 34:1004–1013.

Reed, S.C., E.J. Middlebrooks, and R.W. Crites. 1988. Natural systems for waste management and treatment. McGraw Hill Book Co., New York.

SAS Institute, Inc. 1985. SAS user's guide: Statistics. 5th ed. SAS Inst., Inc., Cary, NC, p. 956.

Sculthorpe, C.D. 1967. The biology of aquatic vascular plants. Edward Arnold, London.

Stephenson, M., G. Turner, P. Pope, J. Colt, A. Knight, and G. Tchobanoglous. 1980. The environmental requirements of aquatic plants. Publ. 65. Appendix A. The State Water Resour. Control Board, Sacramento, CA.

Tchobanoglous, G. 1987. Aquatic plant systems for wastewater treatment: Engineering considerations. p. 27–48. *In* K.R. Reddy and W.H. Smith (ed.) Aquatic plants for water treatment and resource recovery. Magnolia Publ., Orlando, FL.

Teal, J.M., and J.W. Kanwisher. 1966. Gas transport in the marsh grass, *Spartina alterniflora*. J. Exp. Bot. 17:355–361.

van Raalte, M.H. 1940. On the oxygen supply of rice roots. Ann. Jard. Bot. Buitenzorg. 50:99–113.

Weber, A.S., and G. Tchobanoglous. 1985. Rational design parameters for ammonia conversion in water hyacinth treatment systems. J. Water. Pollut. Control Fed. 57:316–323.

Weber, A.S., and G. Tchobanoglous. 1986. Prediction of nitrification in water hyacinth treatment systems. J. Water Pollut. Control Fed. 58:376–380.

Williams, W.T., and D.A. Barber. 1961. The functional significance of aerenchyma in plants. S.E.B. Symp. 15:132–144.

Wolverton, B.C. 1987. Aquatic plants for wastewater treatment: An overview. p. 3–16. *In* K.R. Reddy and W.H. Smith (ed.) Aquatic plants for water treatment and resource recovery. Magnolia Publ., Orlando, FL.