

Oxygen Transport through Aquatic Macrophytes: The Role in Wastewater Treatment

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

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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; Ponnampereuma, 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).

K.R. Reddy and E.M. D'Angelo, Soil Science Dep., 106 Newell Hall, Univ. of Florida, Inst. of Food and Agric. Sci., Gainesville, FL 32611-0313; and T.A. DeBusk, Reedy Creek Energy Services, Inc., P.O. Box 10 000, Lake Buena Vista, FL 32830. Florida Agric. Exp. Stn. Journal Series R-00084. Received 1 Feb. 1989. *Corresponding author.

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 N₂ for 25 min to reduce dissolved O₂ (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 O₂ 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 O₂ transport through the plant along with concurrent O₂ 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 O₂ diffusion. This treatment allowed evaluation of the role of anaerobic microorganisms in reducing BOD₅ 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 O₂ diffusion from the atmosphere in reducing the BOD₅ 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 BOD₅ 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 NH₄-N to maintain the N levels of undiluted effluent. The hypothesis tested was that O₂ transported from the foliage to the rooting zone of the plants would be adequate to support both heterotrophic microbial respiration and nitrification of NH₄-N.

At the end of Experiments 1 and 2, effluent was mixed with a magnetic stirrer, and analyzed for DO, BOD₅, total kjeldahl-N (TKN), NH₄-N, and (NO₃ + NO₂)-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:

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

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 O₂ 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 N₂ 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 O₂ 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 BOD₅, TKN, NH₄-N, and (NO₃ + NO₂)-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 O₂ transported by the plant, because a significant amount of the O₂ transported was subsequently consumed during microbial respiration. Net increase in primary sewage effluent DO (high O₂-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 O₂-demand

Table 1. Dissolved O₂ 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 | |
|--|-------------------------|------------|---------------------------|------------|
| | 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 | | | | |
| <i>Pontederia cordata</i> | 3.2bc | 5.4b | 2.3b | 5.6b |
| Common cattail (<i>Typha latifolia</i>) | 1.7efg | 1.4de | 1.2cd | 1.4ef |
| Common arrowhead | 2.0def | 1.7d | 2.0b | 2.2de |
| <i>Canna flaccida</i> | 2.3cde | 3.1c | 1.8bc | 4.0c |
| <i>Scirpus pungens</i> | 1.2fgh | 1.0e | 0.5e | 0.8ef |
| <i>Scirpus validus</i> | 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 BOD₅ 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 | | |
|--------------------------------|-------------------------|----------------------------|------------|---------------------------|----------------------------|------------|
| | Initial | Barrier | No barrier | Initial | 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 | | | | | | |
| <i>Pontederia cordata</i> | 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 |
| <i>Canna flaccida</i> | 170.5 | 56.0cd | 60.3ef | 56.9 | 77.1a | 78.6ab |
| <i>Scirpus pungens</i> | 137.5 | 30.0f | 54.3f | 48.7 | 2.4c | 46.2c |
| <i>Scirpus validus</i> | 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 BOD₅ used in the experiments ranged from 112 to 179 mg L⁻¹, whereas the initial secondary sewage effluent BOD₅ 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 BOD₅ decreased to less than 27 mg L⁻¹ when treated with pennywort, waterhyacinth, pickerelweed, and arrowhead. The BOD₅ of secondary effluent was reduced

below 10 mg L⁻¹ by the above species and by *Scirpus validus*.

The BOD₅ is a "measurement of the total O₂ required for the oxidation of organic C and reduced N compounds; along with reduced forms of sulfides and ferrous iron" of the effluent (APHA, 1985). Therefore, O₂ consumption (BOD₅ reduction) plus DO accumulation in the effluent during an 8-d retention period was used as an indicator of total O₂ transport into the effluent by the plants (Tables 3 and 4). Among floating aquatic plants pennywort ranked highest, with an O₂ transport capacity of 13 mg O₂ d⁻¹. Among emergent plants pickerelweed ranked highest, at 12.5 mg O₂ d⁻¹. Moorhead and Reddy (1988) found a correlation between dry root mass and O₂ transport rates into the root zone of aquatic plants, therefore, O₂ 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 | | mg O ₂ d ⁻¹ | mg O ₂ g ⁻¹ root d ⁻¹ |
| | | g (dry wt) plant ⁻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 |
| Waterhyacinth | 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 | | | | | | | |
| <i>Pontederia cordata</i> | 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 |
| <i>Canna flaccida</i> | 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 |
| <i>Scirpus pungens</i> | 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 |
| <i>Scirpus validus</i> | 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 | | mg O ₂ d ⁻¹ | mg O ₂ g ⁻¹ root d ⁻¹ |
| | | g (dry wt) plant ⁻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 |
| Wateryacynth | 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 | | | | | | | |
| <i>Pontederia cordata</i> | 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 |
| <i>Canna flaccida</i> | 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 |
| <i>Scirpus pungens</i> | 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 |
| <i>Scirpus validus</i> | 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 O₂ transport capacity of 116 mg O₂ g⁻¹ root d⁻¹ (Table 3). Oxygen transport by waterhyacinth was 57 mg O₂ g⁻¹ root d⁻¹; whereas, O₂ transport by emergent macrophytes ranged from 3.8 to 24.4 mg O₂ g⁻¹ root d⁻¹. Oxygen transport by plants decreased with decreasing effluent O₂ demand. In this study, it was found that high O₂ 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 O₂ by the microorganisms, and the solubilization of respiratory CO₂ into the effluent (Raskin and Kende, 1985). Plants cultured in secondary effluent (low O₂-demand effluent) exhibited an O₂ transport capacity of 13 to 26 mg O₂ g⁻¹ root d⁻¹ for floating aquatic plants, and of 2 to 14 mg O₂ g⁻¹ root d⁻¹ for emergent aquatic plants.

Oxygen transport directly through the plants accounted for greater than 90% of the total O₂ transported into the effluent. Less than 10% of the total effluent O₂ diffused directly from the atmosphere.

Reduction in effluent NH₄-N and TKN as influenced by O₂ transport through the plants is shown in Tables 5 and 6. Initial NH₄-N of the primary sewage effluent was between 17 to 40 mg L⁻¹, whereas the secondary sewage effluent was spiked with NH₄-N to obtain the same range. Effluent (NO₃ + NO₂)-N was low for all treatments.

Biological versus Mechanical Aeration (Experiment 3)

Aquatic plants effected similar levels of wastewater BOD₅ 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 | | |
|--------------------------------|-------------------------|------------------------------|------------|---------------------------|------------------------------|------------|
| | Initial | Barrier | No barrier | Initial | 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 |
| Wateryacynth | 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 | | | | | | |
| <i>Pontederia cordata</i> | 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 |
| <i>Canna flaccida</i> | 28.6 | 36.6cd | 32.0cde | 32.1 | 30.8cd | 36.2abcd |
| <i>Scirpus pungens</i> | 40.5 | 6.1fg | 14.7cde | 40.0 | 13.3ef | 20.1e |
| <i>Scirpus validus</i> | 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 | | |
|--------------------------------|-------------------------------|--------------------------|------------|-------------------------------|--------------------------|------------|
| | Initial mg L ⁻¹ | Barrier % TKN removal | No barrier | Initial mg L ⁻¹ | Barrier % TKN removal | No barrier |
| Floating aquatic plants | | | | | | |
| Pennywort | 24.3 | 38.5cd* | 42.9bc | 27.8 | 4.2f | 24.8de |
| Waterhyacinth | 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 | | | | | | |
| <i>Pontederia cordata</i> | 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 |
| <i>Canna flaccida</i> | 39.5 | 37.6cd | 37.6cd | 39.9 | 35.2bc | 38.9abc |
| <i>Scirpus pungens</i> | 52.5 | 9.6f | 17.0e | 45.8 | 11.0ef | 14.8ef |
| <i>Scirpus validus</i> | 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 BOD₅ of the effluent (70% reduction during the first 5 d). During the same period, mechanical aeration also reduced BOD₅ by about 70%. After approximately 10 d, 90% of the BOD₅ was reduced in all treatments and there was no significant difference between biological aeration and mechanical aeration. The first-order BOD₅ 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 BOD₅ removal rate constant was 0.0023

h⁻¹ for atmospheric diffusion into the primary sewage effluent.

Complete conversion of primary effluent NH₄-N to (NO₃ + NO₂)-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 NH₄-N was also lost from the plant treatments (Fig. 2b), but no effluent (NO₃ + NO₂)-N was measured (Fig. 3). The first-order NH₄-N removal rate constants were from 0.0024 to 0.0107 h⁻¹ ($r^2 = 0.953-0.982$) for biological aeration. Sigmoidal NH₄-

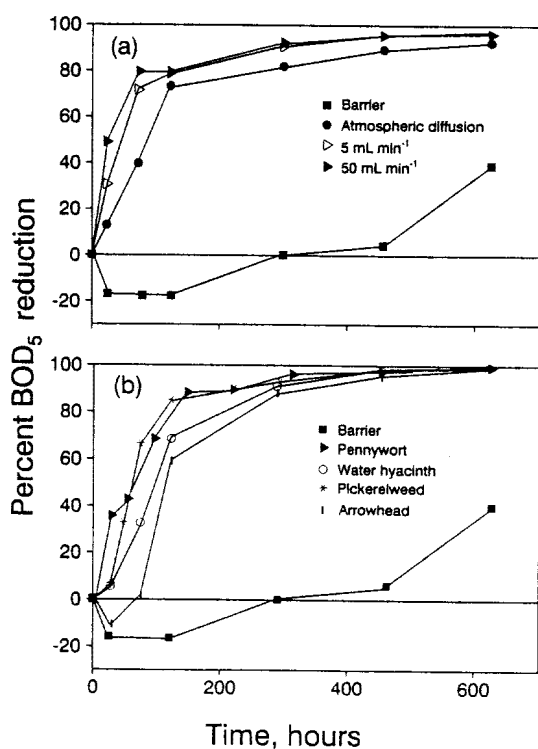


Fig. 1. Effect of (a) mechanical aeration (initial BOD₅ = 181 mg L⁻¹) and (b) biological aeration (initial BOD₅ = 146 mg L⁻¹) on the BOD₅ reduction of primary sewage effluent. Barrier = the effluent isolated from the atmosphere. Mechanical aeration = bubbling air into the effluent at pre-determined flow rates. Atmospheric diffusion = open flasks allowing atmospheric air diffusion into the effluent. Biological aeration = O₂ transport only through the plants into the effluent. Each value represents the mean of three replicates.

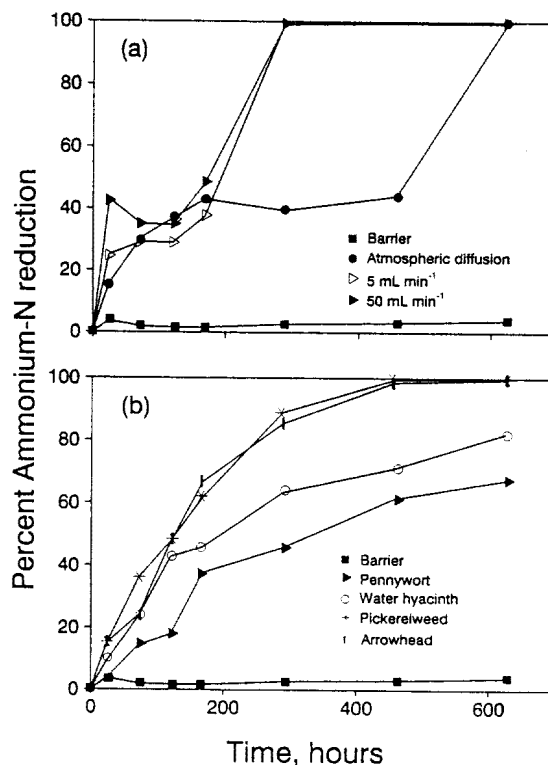


Fig. 2. Effect of (a) mechanical aeration (initial NH₄-N = 23 mg L⁻¹) and (b) biological aeration (initial NH₄-N = 26 mg L⁻¹) on the BOD₅ reduction of primary sewage effluent. Barrier = the effluent isolated from the atmosphere. Mechanical aeration = bubbling air into the effluent at pre-determined flow rates. Atmospheric diffusion = open flasks allowing atmospheric air diffusion into the effluent. Biological aeration = O₂ transport only through the plants into the effluent. Each value represents the mean of three replicates.

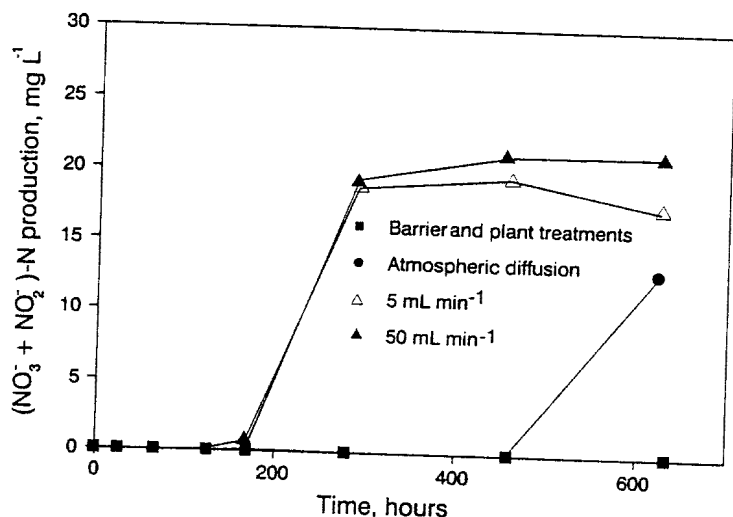


Fig. 3. Effect of mechanical and biological aeration on $(\text{NO}_3 + \text{NO}_2)\text{-N}$ production in primary sewage effluent. Barrier = the effluent isolated from the atmosphere. Mechanical aeration = bubbling air into the effluent at pre-determined flow rates. Atmospheric diffusion = open flasks 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 $\text{NH}_4\text{-N}$ was probably due to NH_3 volatilization, with the subsequent $\text{NH}_4\text{-N}$ 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 $\text{NH}_4\text{-N}$ 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 $\text{NO}_3\text{-N}$ 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 $\text{NH}_4\text{-N}$, 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 $\text{NH}_4\text{-N}$ nitrified (Barnes and Bliss, 1983). The O_2 transport capacities of pennywort and

hyacinth are 27.5 and 10.1 mg $\text{O}_2 \text{ g}^{-1}$ 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 $\text{NH}_4\text{-N ha}^{-1} \text{ d}^{-1}$ would be nitrified in pennywort- and hyacinth-based water treatment systems, respectively. Hauser (1984) measured removal rates of about 17 kg $\text{NH}_4\text{-N ha}^{-1} \text{ d}^{-1}$ at 3-d retention periods, whereas Weber and Tchobanoglous (1985) measured removal rates of about 35 kg $\text{NH}_4\text{-N ha}^{-1} \text{ d}^{-1}$ 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 $\text{NH}_4\text{-N}$ had occurred within 12 d, with $(\text{NO}_3 + \text{NO}_2)\text{-N}$ remaining in the effluent for the duration of the experiment. For the plant treatments, similar effluent $\text{NH}_4\text{-N}$ losses were measured, but negligible $(\text{NO}_3 + \text{NO}_2)\text{-N}$ was measured. Both denitrification of $\text{NO}_3\text{-N}$ to N_2 in effluent anaerobic zones, and plant assimilation of effluent $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$, 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 $^{15}\text{NH}_4\text{-N}$ 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 its 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 O₂ source (the atmosphere) to the apical root section (Luxmoore and Stolzy, 1972). In addition to O₂, 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, O₂ transport capacity as well as plant assimilation should be considered as important design criteria for aquatic plant-based wastewater-treatment systems.

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