Related Factors in Estuarine Ecosystems," International Wetlands Conference, New Delhi, India (1981), pp. 375–387.
4. Jensen, H. Z. "Actinomycetes in Danish Soils," *Soil Sci.* 30:59–77 (1930).
5. Martin, J. P. "The Use of Acid, Rose Bengal, Streptomycin in the Plate Count Method for Estimating Soil Fungi," *Soil Sci.* 69:215–233 (1950).
6. Portier, R. J. "Correlative Field and Laboratory Microcosm Approaches in Ascertaining Xenobiotic Effect and Fate in Diverse Aquatic Microenvironments," Ph.D. dissertation, Louisiana State University, Baton Rouge, LA (1982).
7. Holm-Hansen, O., and C. R. Booth. "The Measurement of Adenosine Triphosphate in the Ocean and Its Ecological Significance," *Limnol. Oceanog.* 11:510–519 (1966).
8. Karl, D. M. "Cellular Nucleotide Measurements and Applications in Microbial Ecology," *Microbiol. Rev.* 44:739–796 (1980).
9. Tabatabai, M. A., and J. M. Bremner. "Use of p-Nitrophenol Phosphate for Assay of Soil Phosphatase Activity," *Soil Biol. Biochem.* 1:301–307 (1969).
10. Atlas, R. M., D. Pramer, and R. Bartha. "Assessment of Pesticide Effects on Nontarget Soil Microorganisms," *Soil Biol. Biochem.* 10:231–239 (1977).
11. Bartha, R., P. Lanzilotta, and D. Parmer. "Stability and Effects of Some Pesticides in Soil," *Appl. Microbiol.* 15:67–75 (1967).
12. Stevenson, L. H., T. H. Crzanowski, and C. W. Erkenbrecher. "The Adenosine Triphosphate Assay: Conceptions and Misconceptions," American Society of Testing and Materials Special Technical Publication 695 (1979), pp. 99–116.
13. Portier, R. J., H. M. Chen, and S. P. Meyers. "Environmental Effect and Fate of Selected Phenols in Aquatic Ecosystems Using Microcosm Approaches," *Devel. Ind. Microbiol.* 24:409–424 (1982).
14. Portier, R. J., and S. P. Meyers. "Coupling of In Situ and Laboratory Microcosm Protocols for Ascertaining Fate and Effect of Xenobiotics," *Toxicity Testing Using Bacteria,* B. J. Dutka and D. Liu, Eds. (New York: Marcel Decker, 1983), pp. 345–379.

38d Secondary Treatment of Domestic Wastewater Using Floating and Emergent Macrophytes

T. A. DeBusk, P. S. Burgoon, and K. R. Reddy

INTRODUCTION

Recent studies in Florida demonstrated that shallow ponds containing large-leaved floating macrophytes, such as pennywort *(Hydrocotyle umbellata)* and water hyacinth (*Eichhornia crassipes*), can remove biochemical oxygen demand (BOD_5) from domestic wastewaters at high rates (100–200 kg/ha/day).[1,2] However, because neither pennywort nor water hyacinth are tolerant of prolonged subfreezing temperatures, treatment systems that utilize these species are limited in year-round operation to the southernmost regions of the United States. For temperate climates, some success has been reported in using gravel-bed systems for treating wastewaters.[3] Gravel-bed systems (GBS) consist of gravel-filled trenches planted with one or more species of emergent macrophytes. Wastewater is usually passed through GBS in a subsurface flow to eliminate problems associated with surface ponding (mosquito production, odors).

Comparative data are not available on the utility of GBS and floating aquatic macrophyte-based treatment systems (FAMS) for providing secondary treatment of domestic wastewater. Therefore, we examined BOD_5 and suspended solids (SS) removal rates from primary effluent using floating and emergent macrophytes cultured in pond and gravel-bed systems.

METHODS

This study was conducted in central Florida using 3000-L outdoor raceways fed primary domestic effluent at a hydraulic loading of 10 cm/day. During November 1987, four treatments were established in duplicate tanks: a gravel (1–3 cm river rock) filled bed with no macrophytes; a gravel bed planted with swordgrass (*Scirpus pungens* = *S. americanus*); a gravel bed planted with

Table 1. Wastewater Biochemical Oxygen Demand (BOD_5) and Suspended Solids (SS) Concentrations in Raceways Containing Floating and Emergent Macrophytes

Sample Location	Plant/ Substrate[a]	BOD_5 (mg/L)	SS (mg/L)
Influent	—	169	44
Effluent	Pennywort/FAMS	27	4
Effluent	Arrowhead/GBS	43	15
Effluent	Swordgrass/GBS	56	16
Effluent	None/GBS	62	19

Note: Values represent means of weekly measurements (duplicate tanks) collected over a six-month period. Average raceway influent contaminant loadings were 172 kg BOD_5 and 45 kg SS/ha/day.
[a]FAMS = floating macrophyte system; GBS = gravel-bed system.

arrowhead (*Sagittaria latifolia*); and an open water system stocked with the floating macrophyte pennywort (*Hydrocotyle umbellata*).

BOD_5 and SS concentrations were measured in grab samples collected weekly from tank effluents.[4] Influent wastewater BOD_5 and SS concentrations were measured twice weekly during the six-month study (November 1987 to April 1988). Each month, plant tissues harvested from within three randomly placed 0.25 m² quadrats were dried (72 hr at 60°C) and weighed to provide a measure of shoot standing crop.

RESULTS AND DISCUSSION

Greatest reductions in wastewater contaminant concentrations were attained in raceways containing the floating macrophyte pennywort (Table 1). BOD_5 and SS removal rates in pennywort raceways averaged 145 and 41 kg/ha/day, respectively, during the six-month study. Contaminant removal rates in gravel-bed systems were highest in raceways containing arrowhead, followed by those containing swordgrass, and those without vegetation (Table 1). The BOD_5 removal rates observed in arrowhead and nonvegetated raceways (115 kg and 98 kg/ha/day, respectively) are higher than the mean annual removal rates of 53 kg BOD_5 and 39 kg BOD_5/ha/day reported for bulrush *(Scirpus validus)* and nonvegetated gravel beds in California.[5]

While mean treatment performance of the GBS was poorer than that of pennywort tanks, effluent quality in the raceways containing gravel gradually improved during the study. Indeed, following six months of operation, effluent wastewater BOD_5 and SS concentrations from the arrowhead raceways were similar to those obtained in the pennywort systems (Figure 1).

Shoot standing crop in the GBS systems increased sharply from the period December 1987 to April 1988 (from 0.18 to 1.31 kg/m² for arrowhead and 0.03 to 1.27 kg/m² for swordgrass). A concomitant increase in root biomass also was observed in these systems during this period. Although this suggests a positive correlation between plant standing crop (e.g., root penetration into the gravel bed) and treatment efficiency, it should be noted that effluent BOD_5

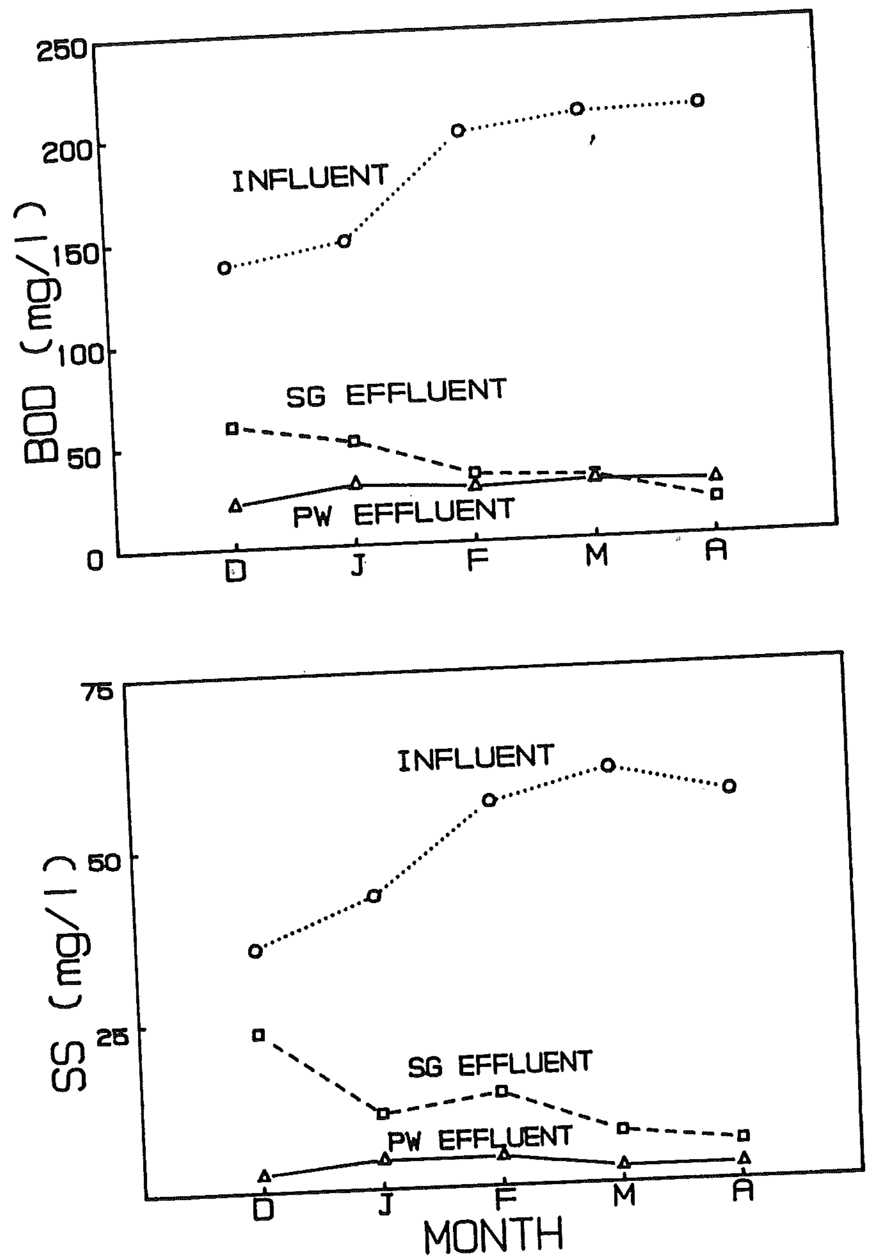

Figure 1. Monthly mean influent and effluent wastewater BOD_5 (top) and SS (bottom) concentrations in raceways containing the macrophytes arrowhead (SG) and pennywort (PW).

and SS concentrations in the unvegetated gravel bed also improved during the six-month study (from 86 mg BOD_5/L in November 1987 to 26 mg/L in April 1988). Apparently, several months are required for development of full treatment capacity in both vegetated and unvegetated beds. This time lag may represent a colonization period for bacteria throughout the gravel system.

The efficiency of floating macrophytes in removing BOD_5 from primary effluent is related to their capability of transporting O_2 from the foliage to the rhizosphere.[1] Oxygen transport rates may also dictate BOD_5 removal rates of emergent species cultured in gravel. In laboratory studies, we observed oxygen transport rates of 112, 19, and 4 mg O_2/g(root)/day for pennywort, arrowhead, and swordgrass, respectively. It is difficult to extrapolate such measurements of O_2 transport by aquatic macrophytes to field conditions because of wide interspecific and intraspecific variability in plant (root) morphology and standing crop. Moreover, little is known of the effects of physiological (e.g., plant age) and environmental parameters on O_2 transport in aquatic plants.

The results of this study demonstrate a gradual improvement in treatment efficiencies of vegetated and nonvegetated GBS during the initial six months of operation. This increased efficiency appears to be related to bacterial colonization in the gravel bed. In contrast, FAMS appear to operate at peak efficiency immediately following startup. Although FAMS have been shown to provide secondary treatment of domestic effluent for several years without operational problems, questions remain regarding the long-term performance of GBS. For example, it is unknown whether treatment efficiency becomes impaired by the accumulation of wastewater-borne solids and plant detritus, which can clog the bed and cause short-circuiting. Moreover, the relation between plant harvest and contaminant removal in GBS is unknown. To facilitate design and operation of GBS, effects of wastewater loading rate, plant species, and harvest regime on the removal of various wastewater contaminants should be investigated.

ACKNOWLEDGMENTS

This study was supported in part by a grant entitled "Methane from Community Wastes" from the Gas Research Institute, Chicago, Illinois to Walt Disney Imagineering (contract no. 5082-223-0762).

REFERENCES

1. DeBusk, T. A., and K. R. Reddy. "BOD Removal in Floating Aquatic Macrophyte-Based Treatment Systems," *Water Sci. Technol.* 19:273–279 (1987).
2. DeBusk, T. A., and K. R. Reddy. "Wastewater Treatment Using Floating Aquatic Macrophytes: Contaminant Removal Processes and Management Strategies," in *Aquatic Plants for Water Treatment and Resource Recovery,* K. R. Reddy and W. H. Smith, Eds. (Orlando, FL: Magnolia Publishing Inc., 1987), pp. 643–656.

3. Brix, H. "Treatment of Wastewater in the Rhizosphere of Wetland Plants—The Root Zone Method," *Water Sci. Technol.* 19:107–118 (1987).
4. *Standard Methods for the Examination of Water and Wastewater,* 16th ed. (Washington, DC: American Public Health Association, 1985).
5. Gersberg, R. M., B. V. Elkins, S. R. Lyon, and C. R. Goldman. "Role of Aquatic Plants in Wastewater Treatment by Artificial Wetlands," *Water Res.* 20:363–368 (1986).