VEGETATED SUBMERGED BEDS WITH ARTIFICIAL SUBSTRATES. I: BOD REMOVAL

By Peter S. Burgoon,¹ Thomas A. DeBusk,² K. R. Reddy,³ and Ben Koopman,⁴ Member, ASCE

ABSTRACT: Settled wastewater was batch fed into 22-L microcosms containing monocultures of the emergent aquatic plants Sagittaria latifolia, Scirpus pungens, Phragmites australis, and Typha latifolia. Plants were cultured in 1.25-cm gravel, and 2.5- and 5.0-cm plastic trickling filter media, with specific surface areas of 394, 279, and 138 m²/m³, respectively. Microcosm performance was evaluated in terms of the percent of influent biochemical oxygen demand (BOD) load removed. BOD removals were evaluated at loads ranging between 2 and 24 g BOD/m²·day. Nonvegetated microcosms performed equivalently to vegetated microcosms over the range of BOD loads tested. Plastic was equivalent to gravel at low loads, but was inferior at higher loads. This was attributed to the higher specific surface area of the gravel and poorer plant growth in plastic. None of the plant species was consistently superior to the others in terms of BOD removal. First-order BOD-removal rate coefficients for these batch-loaded systems were higher than those reported for continuous-flow systems.

INTRODUCTION

Vegetated submerged beds (VSBS) are a type of constructed wetland that has shown considerable promise for domestic wastewater treatment (Reed et al. 1988). A typical VSB consists of a lined channel filled with porous media (soil or gravel) supporting the growth of reeds, rushes, or other emergent aquatic plants. Influent wastewater flows laterally through the bed with the water level maintained 2–4 cm below the surface of the media.

Rooting media having a high specific surface area should be preferable for wastewater treatment in VSBS, as these maximize the microbial population that can be maintained in the bed. Soils have high specific surface areas but low hydraulic conductivities. Soil pores are small and tend to become clogged with biomass, causing wastewater to flow over the surface of the wetland instead of through the plant root zone (Bucksteeg 1987; Brix and Scheirup 1988). Plastic trickling-filter media have been recommended by Wolverton (1982) as a promising approach because of their relatively high specific surface area and high porosity. Large gravels (5–7 cm) with low specific surface areas (50 m²/m³) are generally used in trickling filters (Metcalf and Eddy 1979). The specific surface area of the gravel increases considerably with smaller diameter stones; however, smaller stones have lower hydraulic conductivities and smaller pore size.

The presence of emergent aquatic plants in submerged gravel beds has been reported as beneficial to wastewater treatment (DeJong 1976; Spangler

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394
et al. 1976; Wolverton 1982; Gersberg et al. 1983; Wolverton et al. 1983; Gersberg et al. 1986). This effect may be attributable to the ability of aquatic plants to translocate oxygen into the root zone (Armstrong 1964; Teal and Kanwisher 1966; Green and Etherington 1977; Dacey 1980; Armstrong and Armstrong 1988; Grosse 1989). Transport of oxygen into the root zone augments bacterial oxidation of organic carbon and nitrification. The ability to transport oxygen differs among plant types. *Scirpus validus* has been found to be the best emergent aquatic plant for augmenting removal of nitrogen and BOD (Finnlayson and Chick 1983; Gersberg et al. 1986). Recent research in Florida (Reddy et al. 1990) has shown that common arrowhead (*Sagittaria latifolia*) and swordstem bulrush (*Scirpus pungens*) are good candidates for wastewater treatment systems due to their ability to transport oxygen to the root zone.

The objectives of this study were to determine: (1) The effect of three types of rooting media (substrate) on BOD removal, with particular attention to the effects of the specific surface area of the substrate; and (2) the suitability of four different emergent aquatic plants for use in VSBs under Florida climatic conditions. These included two species commonly used in VSBs (*Typha latifolia* and *Phragmites australis*) and two species not previously evaluated (*Scirpus pungens* and *Sagittaria latifolia*).

**Methods and Materials**

A quartz river gravel (1.25 cm in diameter) and two types of plastic trickling filter media (Jaeger Tri-Pack, Jaeger Products, Spring, Texas) were selected for use as substrates (Table 1). Substrates were poured into 22-L opaque cylindrical pots, which were shaken to aid consolidation. The pots were filled to a final depth of 30 cm. A total of 48 pots were used: 18 with gravel, 15 with 2.5-cm plastic Tri-pack, and 15 with 5.0-cm Tri-pack. The pots were housed within a greenhouse located adjacent to the University of Florida's wastewater treatment plant.

Three pots were used with each combination of plant species and substrate (*T. latifolia* was planted only in the gravel). Three pots of each substrate were nonvegetated and used as controls. Planting densities were 35.5 plants/m² for *S. pungens* and *P. australis*, and 11.8 plants/m² for *S. latifolia* and *T. latifolia*.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Total pore volume/pot (L)</th>
<th>Specific surface area (m²/m³)</th>
<th>Porosity (%)</th>
<th>Surface area/bucket (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>River gravel</td>
<td>6.4</td>
<td>394.0</td>
<td>32</td>
<td>6.8</td>
</tr>
<tr>
<td>Tri-Packs</td>
<td>2.5 cm</td>
<td>11.3</td>
<td>278.7</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>5.0 cm</td>
<td>14.2</td>
<td>137.8</td>
<td>70</td>
</tr>
</tbody>
</table>

*a Surface area per unit bulk volume of substrate.

*b Based on volume displacement and estimated surface area of gravel.

*c As reported by manufacturer (Jaeger Tri-Packs, Inc., Fountain Valley, Calif.).

*d Porosity of substrates calculated by displacement of water.
Plants were acclimated to full-strength settled domestic wastewater over a period of three weeks, starting May 1, 1987. The wastewater effluent was pumped a distance of about 100 m from the University of Florida wastewater treatment plant.

Evapotranspiration (ET) was measured for one replicate each of the gravel and 5.0-cm plastic substrate treatments (i.e., one of the S. latifolia/gravel replicates, one of the S. latifolia/5.0-cm plastic replicates, etc.). The change in water depth throughout a loading cycle, as well as the cross-sectional area of the pot and porosity of the substrate, was used to compute the volumetric water loss.

Evaluation of treatment performance was carried out in three phases, corresponding to target hydraulic loading rates (HLRs) of 4.7 cm/day (low), 9.4 cm/day (medium), and 18.8 cm/day (high). The lowest HLR is equivalent to that used by Gersberg et al. (1986) to achieve high BOD and N removal in a VSB. The first phase extended from May 22 to August 10 (76 days), the second from August 11 to October 7 (56 days), and the third from October 8 to December 3 (57 days). Midday air temperatures within the greenhouse varied from 30° C to 40° C during the first and second study phases, and from 20° C to 30° C during the third study phase. Target HLRs were attained by varying the length of time between wastewater applications according to

\[
HLR = \frac{pD}{T_c} \tag{1}
\]

where \( T_c \) = loading cycle period (day); \( p \) = porosity of substrate; \( D \) = depth of substrate in pots (cm); and HLR is in units of cm/day. Table 2 presents the relationship between \( T_c \) used with the substrates and the target HLRs.

During each of the study phases, influent and effluent samples were collected through three consecutive loading cycles for each microcosm. Sampling was begun after plants reached a density and height (about 1.5 m) common in natural stands. Influent samples were taken from the microcosm distribution lines immediately before the pots were filled with wastewater. The wastewater was retained in the pots for a length of time equal to the \( T_c \) being evaluated. Effluent samples were taken from the pots immediately before drawdown, prior to the next loading cycle. Samples were refrigerated at 4° C, and analyzed for BOD\(_5\) (method 507, Standard methods 1985) within 24 hours.

The presence of plant roots in the substrates had a significant effect on

<table>
<thead>
<tr>
<th>Target hydraulic loading rate (cm/day) (1)</th>
<th>Substrate</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gravel, ( T_c ) (days) (2)</td>
<td>2.5-cm Tri-Pack, ( T_c ) (days) (3)</td>
<td>5.0-cm Tri-Pack, ( T_c ) (days) (4)</td>
<td></td>
</tr>
<tr>
<td>4.7</td>
<td>2.0</td>
<td>3.5</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>9.4</td>
<td>1.0</td>
<td>1.8</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>18.8</td>
<td>0.5</td>
<td>0.9</td>
<td>1.1</td>
<td></td>
</tr>
</tbody>
</table>

396
the volume of wastewater exchanged. To quantify this effect, plants were sacrificed to allow measurement of root biomass at the end of the last study phase. The final volume of water in the buckets was measured before the roots were harvested. Root development increased slightly in all the vegetated pots as the study progressed. Based on pore volume measurements and plant observation, it was assumed that root mass changed by 8% for *Sagittaria* and *Typha*, and 2% for *Scirpus* and *Phragmites*. Thus, root mass (and thus displacement of water by roots) can be assumed to have been greatest during the third study phase and less during the first two phases. BOD$_5$ load (i.e., influent BOD$_5$ flux) was calculated by

$$\text{BOD}_5 \text{ load} = \frac{C_i V_i}{A T_e}$$  \hspace{1cm} (2)

where $C_i =$ influent BOD$_5$ concentration (g/m$^3$); $V_i =$ influent wastewater volume (m$^3$); and $A =$ cross-sectional area of pot (m$^2$). The effluent BOD$_5$ flux was calculated from

$$\text{Effluent BOD}_5 \text{ flux} = \frac{C_f (V_i - V_e)}{A T_e}$$ \hspace{1cm} (3)

where $C_f =$ BOD$_5$ concentration at the end of a $T_e$; and $V_e =$ volume of water lost due to evapotranspiration (m$^3$). The mass removal rate of BOD$_5$ is equal to the difference between the influent and effluent BOD$_5$ flux.

First-order removal rate coefficients were calculated for the pots using

$$k = \frac{\ln \left( \frac{C_f}{C_i} \right)}{T_e}$$ \hspace{1cm} (4)

This is a common model used to design VSBs for BOD removal (Reed et al. 1988) and will allow comparison with current literature values.

Statistical analysis of results was performed with Statistical Analysis System version 6.03 for personal computers, using a general linear models procedure.

**RESULTS**

**Plant Growth**

Detailed information on the growth rates and biomass production of the plants in the respective substrates is given in Burgoon et al. (1991). *Phragmites* grew well in each of the substrates tested. (*Typha* grew well in gravel, the only substrate it was planted in.) *Sagittaria* grew well in the alternative substrates, but, in plastic, was susceptible to heat stress when daytime greenhouse temperatures were greater than 38° C. During the latter part of the second phase of the study, five of the six *Sagittaria* plants in plastic media were severely infected by a fungus and lost a large proportion of their foliage. Four of the infected plants recovered following regular foliar applications of a commercial fungicide (Benomyl). Initial growth of *Scirpus* in gravel was good, but regrowth following harvests was poor. *Scirpus* grew poorly in plastic during all three phases of the study. It is likely that different
growth rates of these plants will have influenced evapotranspiration rates and, possibly, BOD removals.

**Evapotranspiration**

The highest rates of evapotranspiration (ET) were for the *Sagittaria* planted in gravel during the medium (38.9 mm/day) and high (40.3 mm/day) loading rates (Table 3). In *Sagittaria* systems, water loss due to ET during the low HLR was 36% (2.34 L) of the pore volume in gravel ($T_c = 2$ days), and 28% (3.93 L) of the pore volume in plastic ($T_c = 4.3$ days). In the gravel substrate during the high HLR test, ET loss for *Typha* (3.11 L) was higher than for *Sagittaria* (2.34 L). During all of the HLR tests, however, the *Sagittaria* transpired more water than *Phragmites* or *Scirpus*. During all three HLRs, the water loss from *Phragmites* systems with plastic was higher than from those containing gravel. This was due to the longer $T_c$ for plastic substrates.

**General Performance of Microcosms**

The performance of the microcosms is summarized in Tables 4, 5, and 6. These tables give the actual hydraulic loading rates and corresponding BOD loading rates, as well as BOD removals and effluent BOD concentrations. BOD loads were not in strict proportion to the HLRs. This is because of seasonal variations in influent wastewater strength, particularly during the summer when the low student census resulted in a weak wastewater.

The actual HLRs varied somewhat from the target values because of differences in root development among the different plants. This created some nonuniformity of influent BOD loads at the respective target HLRs. The degree of nonuniformity was insignificant in all substrates at the low HLR. At the intermediate and high HLRs, it was significant between the nonvegetated and vegetated pots containing gravel.

The mean BOD$_5$ concentration of microcosm effluents were within secondary effluent standards (30 g/m$^3$) at all loading rates and plant/substrate combinations tested. They ranged from less than 3 g/m$^3$ at the lowest target HLR (4.7 cm/day) to a range of 8–26 g/m$^3$ at the highest target HLR (19

| TABLE 3. Evapotranspiration in Gravel and 5.0-cm Plastic Substrates |
|------------------------|-----------------|----------------|----------------|
|                        | HLR (cm/day)    |                |                |
|                        | 4.7 (mm/day)    | 9.4 (mm/day)   | 18.8 (mm/day)  |
|                        | (2)             | (3)            | (4)            |
| **(a) Gravel**         |                 |                |                |
| *Phragmites*           | 8.6             | 16.3           | 20.4           |
| *Sagittaria*           | 40.3            | 38.9           | 27.1           |
| *Scirpus*              | 6.7             | 8.8            | 21.6           |
| *Typha*                | 11.5            | 30.7           | 36.0           |
| No plants              | 1.9             | 1.4            | 4.7            |
| **(b) Plastic (5.0 cm)** |                |                |                |
| *Phragmites*           | 9.1             | 10.8           | 12.3           |
| *Sagittaria*           | 22.6            | 21.6           | 15.7           |
| *Scirpus*              | 1.5             | 2.5            | 7.9            |
### TABLE 4. BOD Removal at Target Hydraulic Loading Rate 4.7 cm/d*

<table>
<thead>
<tr>
<th>Substrate/plant</th>
<th>Actual HLR(^a) (cm/day)</th>
<th>Influent BOD Flux(^b) g/(m(^2)-day)</th>
<th>Coefficient of variation (4)</th>
<th>% BOD removal (5)</th>
<th>Effluent BOD g/m(^3) (6)</th>
<th>Coefficient of variation (7)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gravel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No plants</td>
<td>4.8</td>
<td>2.07</td>
<td>9.1</td>
<td>95.6 ± 4.2</td>
<td>2.0</td>
<td>78.9</td>
</tr>
<tr>
<td>Phragmites</td>
<td>4.5</td>
<td>1.91</td>
<td>9.1</td>
<td>97.3 ± 3.0</td>
<td>1.8</td>
<td>90.2</td>
</tr>
<tr>
<td>Sagittaria</td>
<td>4.5</td>
<td>1.91</td>
<td>9.1</td>
<td>97.6 ± 1.1</td>
<td>1.0</td>
<td>45.6</td>
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<tr>
<td>Scirpus</td>
<td>4.7</td>
<td>2.00</td>
<td>9.1</td>
<td>98.6 ± 0.6</td>
<td>1.6</td>
<td>37.6</td>
</tr>
<tr>
<td><strong>Plastic (2.5 cm)</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No plants</td>
<td>4.8</td>
<td>2.07</td>
<td>9.1</td>
<td>95.5 ± 1.8</td>
<td>2.1</td>
<td>33.7</td>
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<tr>
<td>Phragmites</td>
<td>4.6</td>
<td>1.98</td>
<td>9.1</td>
<td>96.9 ± 1.2</td>
<td>1.8</td>
<td>38.8</td>
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<tr>
<td>Sagittaria</td>
<td>4.7</td>
<td>2.01</td>
<td>9.1</td>
<td>95.9 ± 6.1</td>
<td>2.1</td>
<td>62.2</td>
</tr>
<tr>
<td>Scirpus</td>
<td>4.8</td>
<td>2.05</td>
<td>9.1</td>
<td>96.1 ± 2.6</td>
<td>2.6</td>
<td>136.6</td>
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<td><strong>Plastic (5.0 cm)</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>No plants</td>
<td>4.7</td>
<td>2.02</td>
<td>9.1</td>
<td>94.9 ± 2.2</td>
<td>2.3</td>
<td>31.9</td>
</tr>
<tr>
<td>Phragmites</td>
<td>4.6</td>
<td>1.95</td>
<td>9.1</td>
<td>98.1 ± 1.2</td>
<td>1.2</td>
<td>52.2</td>
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<tr>
<td>Sagittaria</td>
<td>4.7</td>
<td>2.01</td>
<td>9.1</td>
<td>96.2 ± 4.9</td>
<td>0.8</td>
<td>36.3</td>
</tr>
<tr>
<td>Scirpus</td>
<td>4.7</td>
<td>1.98</td>
<td>9.1</td>
<td>98.5 ± 0.6</td>
<td>2.2</td>
<td>127.2</td>
</tr>
</tbody>
</table>

*There were no significant (\(p < 0.05\)) differences between treatments.

\(^b\)T. for the gravel, plastic 2.5, and 5.0-cm substrates was 2.0, 3.5, and 4.5 days, respectively.

\(^c\)Mean influent BOD = 42.0 g/m\(^3\) BOD.

The corresponding BOD mass removals were 95% or better at the low HLR and 76–93% at the high HLR.

#### Effect of Emergent Plants

Comparisons of treatment performances are best made in relation to BOD\(_5\) loading, since there was variation of BOD\(_5\) loads at each target HLR. A least-squares, linear regression of BOD mass removal versus BOD mass load for all vegetated gravel media pots is shown in Fig. 1. Also shown in the figure are the data for the nonvegetated gravel pots, which were not used in computing the confidence limits. It can be seen that most of the data from the nonvegetated pots fall within the 95% confidence interval for the vegetated pots. There was no significant superiority of any one plant over another.

#### Effect of Substrate

The effect of substrate on BOD mass removal by vegetated microcosms, regardless of plant type, is shown in Fig. 2. The 95% confidence limits in this figure were calculated using data from the gravel plant microcosms only. BOD removal with vegetated gravel substrates was generally greater and less variable than BOD removal with vegetated plastic substrates.

A similar analysis was carried out using data for Phragmites, which grew well in both the gravel and plastic substrates (Fig. 3). The confidence limits shown in Fig. 3 were computed for Phragmites in gravel only. There was no difference between the substrates at BOD loads of up to 13.0 g/(m\(^2\)-day). At higher loadings, BOD removals with plastic media were more variable than those with gravel, and generally lower. Analysis of performance data
TABLE 5. BOD Removal at Target Loading Rate of 9.4 cm/day

<table>
<thead>
<tr>
<th>Substrate/plant</th>
<th>Actual HLR (cm/day)</th>
<th>Influent BOD Flux (g/(m²·day))</th>
<th>Coefficient of variation</th>
<th>% BOD removal (%)</th>
<th>Effluent BOD g/m³</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Gravel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No plants</td>
<td>9.5</td>
<td>10.42</td>
<td>11.4</td>
<td>89.7 ± 3.9</td>
<td>9.8</td>
<td>41.0</td>
</tr>
<tr>
<td>Phragmites</td>
<td>8.2</td>
<td>8.63</td>
<td>13.1</td>
<td>94.2 ± 1.7</td>
<td>8.0</td>
<td>27.9</td>
</tr>
<tr>
<td>Sagittaria</td>
<td>8.2</td>
<td>8.63</td>
<td>13.1</td>
<td>94.5 ± 1.4</td>
<td>8.3</td>
<td>31.5</td>
</tr>
<tr>
<td>Scirpus</td>
<td>9.1</td>
<td>9.01</td>
<td>13.4</td>
<td>96.5 ± 2.4</td>
<td>4.4</td>
<td>56.9</td>
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<td>Typha</td>
<td>9.1</td>
<td>9.97</td>
<td>11.4</td>
<td>97.9 ± 1.2</td>
<td>4.4</td>
<td>48.4</td>
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<tr>
<td>(b) Plastic (2.5 cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No plants</td>
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<td>8.83</td>
<td>13.2</td>
<td>85.5 ± 2.7</td>
<td>12.6</td>
<td>26.9</td>
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<td>Phragmites</td>
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<td>91.6 ± 4.2</td>
<td>10.0</td>
<td>58.3</td>
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<td>8.83</td>
<td>12.8</td>
<td>87.2 ± 9.1</td>
<td>16.2</td>
<td>60.2</td>
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<tr>
<td>Scirpus</td>
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<td>8.79</td>
<td>13.6</td>
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<td>62.7</td>
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<td>(c) Plastic (5.0 cm)</td>
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<tr>
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<td>8.80</td>
<td>13.1</td>
<td>84.9 ± 6.3</td>
<td>13.2</td>
<td>44.1</td>
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<tr>
<td>Phragmites</td>
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<td>8.49</td>
<td>13.3</td>
<td>91.9 ± 3.2</td>
<td>9.8</td>
<td>44.0</td>
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<td>Sagittaria</td>
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<td>8.64</td>
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<td>84.6 ± 13.2</td>
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<td>90.0</td>
</tr>
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<td>8.59</td>
<td>13.4</td>
<td>92.6 ± 4.0</td>
<td>7.8</td>
<td>49.0</td>
</tr>
</tbody>
</table>

*Mean influent BOD = 97.2 g/m³ BOD.

Tc for the gravel, plastic 2.5, and 5.0-cm substrates was 1.0, 1.8, and 2.3 days, respectively.

When the averages of all treatments within each substrate were compared, gravel was found to be significantly better (p < 0.05) than either plastic substrate.

for Sagittaria in the gravel and plastic media (Fig. 4) gave a similar trend. The increased variability of performance with plastic media can also be seen by comparing the coefficients of variation for BOD removals as reported in Tables 5 and 6.

There were no significant differences in BOD removal among the three substrates when plants were absent (Fig. 5). The confidence limits shown in the figure were computed for gravel with no plants only.

First-Order BOD Removal Coefficients

Removal rate coefficients were calculated for all microcosms in the gravel substrate. The coefficients generally decreased as the Tc increased. Table 7 gives the coefficients calculated for Typha, Phragmites, and the nonvegetated pots during each of the study phases. They were similar in magnitude to first-order BOD removal coefficients calculated using data from Wolverton et al. (1983).

**ANALYSIS**

BOD removal in attached growth systems is generally considered to be facilitated by media with high specific surface area. For example, Jewell and coworkers (1981, 1987) demonstrated improved performance of anaerobic expanded beds with media having specific surface areas as high as 1 \( \times 10^6 \) m²/m³. On the other hand, Young and Yang (1989) found that the performance of an anaerobic, fixed-bed system was independent of specific
TABLE 6. BOD Removal at Target Hydraulic Loading Rate of 18.8 cm/day

<table>
<thead>
<tr>
<th>Substrate/plant</th>
<th>Actual HLR(^a) (cm/day)</th>
<th>Influent BOD Flux(^b) g/(m²·day)</th>
<th>Coefficient of variation (4)</th>
<th>Percent BOD removal (5)</th>
<th>Effluent BOD g/m² (6)</th>
<th>Coefficient of variation (7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No plants</td>
<td>16.2</td>
<td>24.07</td>
<td>0.5</td>
<td>84.9 ± 9.7</td>
<td>1.61</td>
<td>44.2</td>
</tr>
<tr>
<td>Phragmites</td>
<td>16.4</td>
<td>19.05</td>
<td>3.2</td>
<td>93.0 ± 4.3</td>
<td>14.5</td>
<td>61.2</td>
</tr>
<tr>
<td>Sagittaria</td>
<td>16.4</td>
<td>16.95</td>
<td>2.6</td>
<td>89.8 ± 10.3</td>
<td>10.4</td>
<td>74.5</td>
</tr>
<tr>
<td>Scirpus</td>
<td>18.2</td>
<td>23.56</td>
<td>0.5</td>
<td>87.5 ± 5.0</td>
<td>10.8</td>
<td>41.0</td>
</tr>
<tr>
<td>Typha</td>
<td>16.2</td>
<td>22.11</td>
<td>1.9</td>
<td>92.1 ± 2.5</td>
<td>8.1</td>
<td>25.9</td>
</tr>
</tbody>
</table>

(a) Gravel\(^c\)

| No plants       | 18.9                      | 24.33                              | 0.5                         | 80.3 ± 8.1             | 21.6                   | 37.1                      |
| Phragmites      | 17.2                      | 22.26                              | 4.9                         | 79.3 ± 15.1            | 22.0                   | 62.0                      |
| Sagittaria      | 17.9                      | 21.14                              | 3.3                         | 85.5 ± 6.1             | 17.5                   | 38.2                      |
| Scirpus         | 18.6                      | 24.08                              | 0.4                         | 84.3 ± 9.6             | 17.6                   | 51.9                      |

(b) Plastic (2.5 cm)

| No plants       | 19.4                      | 24.94                              | 0.4                         | 76.4 ± 10.3            | 25.6                   | 43.4                      |
| Phragmites      | 18.2                      | 21.42                              | 3.3                         | 82.5 ± 11.9            | 19.5                   | 58.2                      |
| Sagittaria      | 18.6                      | 22.98                              | 2.5                         | 84.5 ± 12.1            | 18.6                   | 73.7                      |
| Scirpus         | 19.2                      | 24.88                              | 0.2                         | 81.5 ± 15.9            | 20.3                   | 75.3                      |

(c) Plastic (5.0 cm)

\(^a\) Mean influent BOD = 127.5 g/m³ BOD.
\(^b\) For the gravel, plastic 2.5, and 5.0 cm substrates was 0.5, 0.9, and 1.1 days respectively.
\(^c\) When the averages of all treatments within each substrate were compared, gravel was found to be significantly better (\(p < 0.05\)) than either plastic substrate.

Surface area over a range of 90–225 m²/m². The results of this study indicate that the specific surface area of the rooting substrate in a VSB exerts a significant influence on BOD removal at BOD loads of 15 g/(m²·day) and higher in vegetated pots. This effect may be due to the available surface area of the media as well as its compatibility with emergent aquatic plants. The study showed that BOD removal was independent of specific surface area in nonvegetated pots. The specific surface area of the roots for a given plant in a VSB may be large enough to significantly increase the specific surface area available for colonization. Based on calculations from data for a mature corn plant (Smika and Klute 1982), we estimate root-specific surface area to be from 3.5 to 6.6 m² in an experimental pot. The surface area of the gravel substrate was about 6.8 m² per pot. Thus, the ability of the plants to grow and develop extensive root mass in the media may be an overriding factor in removal of BOD.

Despite its somewhat inferior properties as a rooting substrate, plastic media merits consideration for use in VSBs if it can increase hydraulic conductivity or reduce clogging. Kickuth (1977) has claimed that the hydraulic conductivity of a VSB will increase as the plant roots become established, but others have documented that low conductivity and clogging can be significant problems. McIntyre (1989) showed that the hydraulic conductivity in a VSB with sand as a rooting medium, and fed a nutrient solution, decreased by 55% over a period of seven months. The gravel beds at Santee Municipal Water Authority, which contain 2–3 cm stones, have clogged near the front end after three years of receiving primary and secondary effluent. Longer
FIG. 1. Effect of Emergent Plants on BOD Removal in Gravel Substrate (Dashed Lines = 95% Confidence Limits for Vegetated Pots)

FIG. 2. Effect of Substrate on BOD Removal in Vegetated Microcosms (Dashed Lines = 95% Confidence Limit for All Plants Grown in Gravel)
FIG. 3. Effect of Substrate on BOD Removal in Microcosms with *Phragmites australis* (Dashed Lines = 95% Confidence Limits for Gravel Substrate)

FIG. 4. Effect of Substrate on BOD Removal in Microcosms with *Sagittaria latifolia* (Dashed Lines = 95% Confidence Limits for Gravel Substrates)
FIG. 5. Effect of Substrate on BOD Removal in Microcosms with No Plants (Dashed Lines = 95% Confidence Limit Intervals for Gravel Microcosms with No Plants)

term studies are needed to determine if plastic media can overcome such problems.

Our results showed that nonvegetated pots were similar in performance to pots containing emergent aquatic plants over a BOD loading range of 2–24 g/(m²·day). This is consistent with previous work by Wolverton (1982), who found that batch-loaded, nonvegetated systems removed amounts of BOD similar to vegetated systems at a BOD load of 4.2 g/(m²·day). However, continuous-flow, vegetated microcosms gave better performance than non-

TABLE 7. Comparison of First-Order BOD-Removal Rate Coefficients between VSBs Operated as Batch and Continuous-Flow Reactors

<table>
<thead>
<tr>
<th>Plant (1)</th>
<th>$T_c$ (days)</th>
<th>Batch Flow</th>
<th>Continuous Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.25°</td>
<td>0.5°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(days$^{-1}$)</td>
<td>(days$^{-1}$)</td>
</tr>
<tr>
<td>$T. latifolia$</td>
<td>5.51</td>
<td>4.14</td>
<td>1.89</td>
</tr>
<tr>
<td>$P. australis$</td>
<td>8.19</td>
<td>4.35</td>
<td>3.20</td>
</tr>
<tr>
<td>No plants</td>
<td>5.51</td>
<td>4.14</td>
<td>2.13</td>
</tr>
</tbody>
</table>

*Wolverton et al. (1983).
**Gersberg et al. (1986).
***This study.
vegetated beds at a BOD load of 5.6 g/(m²·day) (Gersberg et al. 1986).

Reed et al. (1988) noted considerable differences in first-order BOD-removal rate coefficients between bench-scale VSBs operated in a fill and draw mode and field-scale, continuous-flow systems. BOD-removal rate coefficients for our study agree with those from bench-scale studies by Wolverton et al. (1983). These are an order of magnitude greater than the coefficients calculated for field-scale, continuous-flow systems (Table 7). The static hydraulic environment within the batch-loaded reactors, combined with regular draining and flooding, should be conducive for BOD removal since short-circuiting is eliminated, and oxygen is drawn into the root zone. Bowmer (1987) has noted that short-circuiting may impair the performance of continuous flow systems.

Gersberg et al. (1986) found that VSBs planted with Phragmites and Scirpus validus removed significantly more BOD than those containing Typha. They postulated that the poor performance of Typha was due to the bed depth (76 cm) and poor plant growth and suggested that a shallower bed (e.g., 30 cm) would improve performance with Typha. In the present study, it was observed that Typha performed as well as other plants in the 30.5-cm deep pots.

There is a paucity of performance data for Sagittaria latifolia and none for Scirpus pungens in VSBs used for wastewater treatment. Wolverton (1987) found Sagittaria to perform similarly to Typha and Phragmites. We showed in the present research that gravel-filled pots planted with either Sagittaria or Scirpus removed BOD as well as Phragmites australis. Neither Sagittaria nor Scirpus were as healthy as Phragmites when grown in the plastic substrate, however. Use of Sagittaria species may be limited to the subtropics because of their intolerance to cold weather.

CONCLUSIONS

There were no significant differences in removal of BOD₅ among the aquatic plants evaluated, or between vegetated and nonvegetated pots. However BOD₅ removal was more variable for plants grown in the plastic substrate.

Plastic substrates (low specific surface area) were equivalent to gravel (high specific surface area) at low loads [<15 g/(m²·day)], but were inferior at higher loads [15–25 g/(m²·day)].

First-order BOD-removal rate coefficients for these batch-loaded systems are higher than those reported for continuous flow VSBs.

ACKNOWLEDGMENTS

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APPENDIX. REFERENCES


Wolverton, B. C. (1982). “Hybrid wastewater treatment system using anaerobic mi-