Treatment of Presettled Municipal Wastewater Using a Passively Aerated Vertical Bed

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ABSTRACT

A novel pilot-scale passively aerated vertical bed (PAVB) for the treatment of municipal wastewater was investigated. Two modes of PAVB operation were compared. In the first mode, “continuous feeding,” an uninterrupted flow of wastewater was applied to the bed until clogging, followed by a “rest period” to regenerate pore space. During the rest period only passive aeration was provided by recirculation of clean effluent through the bed. In the second mode, “intermittent feeding,” a daily schedule of 8 h of wastewater flow to the bed followed by a rest period of 16 h was employed. The results indicate that continuous operation is advantageous over intermittent operation. A high COD removal rate of about 800 g/m2/day was obtained when the system operated in the “continuous feeding” mode and the COD removal efficiency was about 50%. Clogging of the bed with apparent ponding occurred at a free pore space of 30 to 35% from its initial value. During both continuous and intermittent modes of operation, an irreversible clogging of 40% was observed. Higher organic removal efficiency was achieved by operating three vertical bed units in a series. The overall average COD and BOD reductions in the vertical bed system were 83 and 88%, respectively, with effluent COD concentrations between 50 and 128 mg/L and BOD concentrations were between almost zero and 45 mg/l. In contrast to PAVB for tertiary treatment, no significant advantage was shown in using passive aeration when the PAVB was used for secondary treatment with a relatively large particle size (15 mm).

Key words: vertical flow constructed wetlands; sewage treatment; clogging; rest period; passive aeration

INTRODUCTION

Based on population size, climatic conditions, and socioeconomic considerations, appropriate technology for wastewater treatment in rural areas in the Middle East needs to be reliable, simple, low cost, and low impact. This characterization typically results in land-extensive processes. However, the classical combination of extensive treatment units (i.e., anaerobic ponds/facultative ponds/reservoir) results in water losses due to the high evaporation rates prevailing in the Mediterranean region.

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To reduce land requirements and minimize water losses while maintaining the above requirements, the removal of a major fraction of the organic load should be accomplished using a semi-intensive process prior to polishing by extensive units. To attain the removal of the majority of the initial BOD load, a novel passively aerated vertical bed (PAVB) for the treatment of settled municipal wastewater has been investigated. The investigation was carried out in a pilot scale unit (10 m³) located in the rural Arab town of Sakhnin in Northern Israel.

The PAVB process combines the advantages of the vertical flow wetland concept (minimal energy input, low operational costs, low maintenance, and high reliability) with the high loading rates typically associated with trickling filters. The process is based on convective aeration achieved by a fill-and-draw operational sequence of a vertical flow bed. Sewage, evenly distributed on the top of the bed, trickles through the unsaturated media and accumulates at the bed’s bottom. At a fixed time interval, effluent accumulating at the bed’s bottom is rapidly drained (the draw phase). Each volume discharged from the lower part of the bed is replaced by an equal volume of fresh air introduced through an aeration pipe. The volume of air trapped in the lower bed during rapid drainage is subsequently forced up through the bed during the fill phase and ensures good bed aeration. The theoretical amount of oxygen supplied by the passive pump is 8.75 mmol O₂ per liter effluent drained (280 mg/L O₂). Assuming full oxygen transfer and taking into account cell anabolism, a maximum COD removal of approximately 500 mg/L can be achieved.

The effectiveness of the passive aeration system depends on the relative resistance to air flow between the upper layer of the bed and the aeration pipe. If the resistance to air flow in the upper layer is high, that is, the upper layer consists of small particles, more air will flow via the aeration pipe during effluent discharge. Previous experiments using a PAVB with small media size for the removal of ammonia from secondary municipal effluents containing low BOD and suspended solids (SS) established the advantages of this technology (Green et al., 1998; Lahav et al., 2001). However, small media size in the upper layer to maximize air flow via the aeration pipe for ammonia removal may prove to promote bed clogging when treating municipal wastewaters for BOD removal. Serious bed clogging requires long inactive periods of no wastewater feeding to regenerate and reopen blocked pores and reduces the effectiveness of the process. The objective of this study was, therefore, to assess the efficiency of

![Figure 1. Diagram of passively aerated vertical bed (PAVB). Solid line arrows in the media show water flow and broken line arrows show airflow. (1) Wastewater distribution weir. (2) electrical valves activated by level control: (a) air intake (b) water discharge. (3) Air intake pipe and bottom manifold. (4) Smaller size gravel layer. (5) Coarse gravel layer. (6) Level control.](image)
the PAVB concept for treating secondary municipal wastewater.

MATERIALS AND METHODS

General design of the vertical beds

The pilot unit, constructed from fiberglass, had a cylindrical shape with a height of 2.2 m and a diameter of 2.4 m with an upper surface area of 4.5 m². The unit was filled with two main layers of gravel: the active upper layer consisting of smaller size gravel (15 mm) and occupying 85% of the bed volume and the bottom layer consisting of coarse gravel (5–6 cm) having a much lower resistance to airflow than the upper layer (Fig. 1). The initial porosity of the unit was 0.48. An aeration pipe supplying air to the process traverses the upper layer of media and connects the coarse media layer to the atmosphere. The influent was evenly distributed on top of the upper layer of the bed and drained at the bottom. The bottom of the bed was built with a slope of 1% towards the outlet. A series of perforated drainage pipes lead to the outlet. The outlet size was designed to allow for a flow rate much higher than the inlet flow rate even at very low heads (0.1 m). The intermittent outflow was governed by an electrical valve actuated by a level switch (Fig. 1).

Experimental setup

Two modes of operation were compared: “continuous feeding” mode, and “intermittent feeding” mode. The “continuous feeding” mode was characterized by uninterrupted flow of influent to the bed until clogging was observed. A subsequent rest period was initiated, during which the change in total available pore space was monitored. The total available pore space was assessed weekly by completely filling the bed with treated effluent and subsequently measuring the volume of water that drained from the bed. An additional feeding period started only when no further increase in available pore space was observed. The “intermittent feeding” mode was characterized by predetermined feeding and rest periods: 8 h of feeding followed by a rest period of 16 h. The ratio between the rest and feeding periods was determined by evaluating preliminary results obtained during the “continuous feeding” mode. COD removal rate and clogging patterns were compared to evaluate the performance of the two modes of operation.

A summary of the operational regime, which includes the duration of each treatment and rest period, the hydraulic loading rate (HLR) applied and influent characteristics, is presented in Table 1. The high COD concentration of the wastewater is typical of Arab villages in Israel, resulting from low water consumption per capita, combined with random small industry discharges that are often high in organic content (such as olive oil).

As is often the case in pilot operation, the control over the influent characteristics was limited. Influent was pumped from poorly performing stabilization ponds treating the wastewater of the Sakhnin municipality and occasionally industrial wastes in a random fashion. The result was a very large variation in influent characteristics both in BOD and in suspended solids (SS) concentration. These variation were reflected in the results obtained from the vertical bed.

Analyses

All analyses were made according to Standard Methods (APHA, 1995). COD was determined using the microreflux method and potentiometric titration to deter-

Table 1. Operational parameters for the PAVB

<table>
<thead>
<tr>
<th>Mode of operation</th>
<th>Intermittent</th>
<th>Intermittent</th>
<th>Intermittent</th>
<th>Continuous</th>
<th>Continuous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Average temperature (°C)</td>
<td>19</td>
<td>15</td>
<td>20</td>
<td>16</td>
<td>25</td>
</tr>
<tr>
<td>HLR (m/day)</td>
<td>9a</td>
<td>4.5a</td>
<td>9a</td>
<td>4.5</td>
<td>9</td>
</tr>
<tr>
<td>Influent COD (mg/L)</td>
<td>461 ± 78</td>
<td>559 ± 128</td>
<td>820 ± 127</td>
<td>525 ± 120</td>
<td>536 ± 75</td>
</tr>
<tr>
<td>COD loading rate (g/m²/day)</td>
<td>1383</td>
<td>838</td>
<td>2460</td>
<td>2363</td>
<td>4824</td>
</tr>
<tr>
<td>Influent TSS (mg/L)</td>
<td>83 ± 25</td>
<td>172 ± 97</td>
<td>488 ± 122</td>
<td>124 ± 50</td>
<td>243 ± 38</td>
</tr>
<tr>
<td>TSS loading rate (g/m²/day)</td>
<td>249</td>
<td>258</td>
<td>1464</td>
<td>558</td>
<td>2187</td>
</tr>
<tr>
<td>Treatment period (days)</td>
<td>84</td>
<td>110</td>
<td>35</td>
<td>85</td>
<td>25</td>
</tr>
<tr>
<td>Rest period (days)</td>
<td>integrated</td>
<td>integrated</td>
<td>integrated</td>
<td>23</td>
<td>50</td>
</tr>
</tbody>
</table>

*HLR during the daily 8-h feeding period.
mine the end point. BOD was measured using an Oxitop device (manufacturer: WTW). Total suspended solids (TSS) was measured by weighing filtered (Whatman GFA filter paper) samples after drying for 24 h at 105°C.

RESULTS AND DISCUSSION

When adapting the passively aerated vertical bed for secondary treatment (BOD removal) as opposed to tertiary treatment (nitrification), the design was modified to consist of rather large size gravel of 12–15 mm instead of the 3.5 mm used for nitrification. The aim of increasing media size was to reduce bed clogging by influent suspended solids and heterotrophic biomass accumulation at the expense of the effectiveness of the passive aeration system. In addition to the change in gravel size, a regeneration (rest) period was introduced into the operation cycle to overcome clogging problems. During the rest period, influent supply was stopped and the passive aeration continued to operate by recirculating tap water (or treated effluent). The aim of this active rest period was to declog the bed by hydrolyzing and degrading the suspended matter and biomass that had accumulated in the previous cycle.

Table 2. Performance data for the PAVB

<table>
<thead>
<tr>
<th>Mode of operation</th>
<th>Intermittent 1</th>
<th>Intermittent 2</th>
<th>Intermittent 3</th>
<th>Continuous 1</th>
<th>Continuous 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Effluent COD (mg/L)</td>
<td>326 ± 76</td>
<td>330 ± 61</td>
<td>460 ± 150</td>
<td>274 ± 114</td>
<td>263 ± 56</td>
</tr>
<tr>
<td>COD removed (mg/L)</td>
<td>143 ± 61</td>
<td>228 ± 99</td>
<td>366 ± 25</td>
<td>245 ± 45</td>
<td>267 ± 75</td>
</tr>
<tr>
<td>% COD removed</td>
<td>30</td>
<td>41</td>
<td>40</td>
<td>47</td>
<td>50</td>
</tr>
<tr>
<td>COD removal rate (g/m²/day)</td>
<td>429</td>
<td>342</td>
<td>1,098b</td>
<td>405b</td>
<td>1,102b</td>
</tr>
<tr>
<td>Effluent TSS (mg/L)</td>
<td>54 ± 21</td>
<td>97 ± 35</td>
<td>143 ± 74</td>
<td>59 ± 38</td>
<td>151 ± 19</td>
</tr>
<tr>
<td>TSS removed (mg/L)</td>
<td>29 ± 20</td>
<td>75 ± 63</td>
<td>345 ± 86</td>
<td>68 ± 32</td>
<td>92 ± 45</td>
</tr>
<tr>
<td>% TSS removed</td>
<td>35</td>
<td>44</td>
<td>70</td>
<td>55</td>
<td>38</td>
</tr>
<tr>
<td>TSS removal rate (g/m²/day)</td>
<td>87</td>
<td>112</td>
<td>1,035b</td>
<td>381b</td>
<td>306b, 241b</td>
</tr>
</tbody>
</table>

*Based on the active period only (not including rest period); *b* based on both the active and rest periods.

Figure 2. COD removal during the “intermittent feeding” operation.
“Intermittent feeding” mode

Starting with clean new media, the PAVB was operated in the “intermittent feeding” mode continuously for 229 days. Three periods (intermittent 1, 2, and 3) were defined as listed in Table 1. During the first period of “intermittent feeding” lasting 84 days, a HLR of 9 m/day was applied daily during an 8-h feeding period that was followed by a 16-h rest period. The average total COD (CODt) and TSS influent concentrations were 461 and 83 mg/L, respectively. In the second period (intermittent 2) lasting 110 days, the HLR was reduced to 4.5 m/day. The average influent CODt and TSS concentrations were 559 and 172 mg/L, respectively. The average COD removed during the first two periods of intermittent feeding were 143 and 228 mg/L, respectively, resulting in effluent qualities of 326 and 330 mg COD/L (Table 2, Fig. 2). The respective daily COD removal rates were 429 and 342 g/m²/day. Despite the “built-in” rest period (16 h per day), a gradual reduction in the available pore space was observed (Fig. 3). However, the gradual clogging was slower during the second period (lower influent load) and the pore space stabilized at about 55% of the initial value. At the end of the second period, the HLR was increased again to 9 m/day (during the daily 8-h feeding period) together with an unintentional increase in the influent COD and TSS concentrations to over 800 mg/L and almost 500 mg/L, respectively. As a consequence, the influent COD loading rate increased dramatically during the third “intermittent feeding” period, from an average loading rate of 1,383 and 838 g/m²/day during intermittent 1 and 2 to 2,460 g/m²/day during intermittent 3 (Table 1). Under these conditions the system operated very efficiently with a removal rate during the active period of 1,098 g COD/m²/day and 1,035 g TSS/m²/day (Table 2). However, this high removal efficiency was accompanied by a sharp decrease in pore space, reaching a value of less than 30% of the initial value after 35 days. Ponding was also apparent. A continuous rest period of about 60 days was required to recover clogged pore space (Fig. 4, intermittent 3). Calculating the COD removal rate for the intermittent 3 period, based on both active and rest periods, yields a much lower value of 405 g/m²/day, which is similar to the removal rates observed in intermittent 1 and 2.

“Continuous feeding” mode

The “continuous feeding” mode of operation (period 4) started after a 110-day rest period when the pore space reached a stable value of 60%. A HLR of 4.5 m/day was applied and the average influent concentrations were 525 mg COD/L and 124 mg TSS/L (Fig. 5). The system operated for 85 days until ponding was apparent. The available pore space was found to be constant (60%) during the first 40 days of “continuous feeding” followed by a
gradual decrease to 36% within the next 45 days (Fig. 6). These results can probably be explained by the increase in influent CODt and TSS concentrations during the last 45 days (Fig. 5). The subsequent rest period lasted for only 23 days (Fig. 4, continuous 4) when the pore space reached a stable value of about 60% of the initial value (more details in section “Effectiveness of passive air pump during the rest period”). Based on both active and rest period, the average COD removal rate was 868 g/m²/day (Table 2). At the end of the rest period, an additional “continuous feeding” period began (period 5) with an increased HLR of 9m³/day. The vertical bed op-

Figure 4. Pore space regeneration during rest periods. “Intermittent 3” and “continuous 5” were performed with the passive air pump. In the period of “continuous 4” the passive air pump was disconnected.

Figure 5. Influent characteristics during the “continuous 4” operation.
erated for 25 days until ponding was apparent again. A rest period of 50 days was required to regain 60% of the original pore space. The average COD removal rate during this stage (801 g/m²/day) was similar to that obtained during the previous “continuous feeding” period 4 despite the twofold difference in HLR.

Comparison between “intermittent feeding” and “continuous feeding” modes

The results obtained from the performance of the PAVB in the two different modes of operation (continuous and intermittent cycles) indicate that the “continuous
feeding” mode of operation is advantageous. Despite the large variability in influent concentrations, both COD removal rate and efficiency were much higher using the “continuous feeding” mode. The COD removal rate was about two times higher (Table 2), and the removal efficiency was about 50% as opposed to about 40% during “intermittent feeding” mode. Similar results regarding the advantage of “continuous feeding” over “intermittent feeding” were obtained using a passively aerated vertical bed for the treatment of dairy wastewater (Green et al., 2004).

The effectiveness of the passive air pump during “continuous feeding”

The effect of the passive air pump on COD removal and regeneration efficiencies in the vertical bed was evaluated. When adapting the passively aerated vertical bed for secondary treatment (BOD removal) as opposed to tertiary treatment (nitrification), one of the major modifications was the use of larger size gravel of 12–15 mm instead of the 3.5 mm gravel used for the nitrification beds (Lahav et al., 2001). The rationale was to overcome clogging problems associated with municipal wastewater treatment at the expense of a reduction in the effectiveness of the passive aeration system.

During active “continuous feeding” in period 4 (lasting 85 days), passive air pump operation was discontinued for approximately 2 weeks. The COD removal was monitored and almost no difference was observed between vertical bed operation with and without the pump (Fig. 7, days 34 to 49). The average COD removal during the first 33 days (with pump) was 244 mg/L. During the subsequent 15 days without pump (days 34–49), the removal was 237 mg COD/L. Finally, in the last 24 days with the pump connected again, the COD removal was...
258 mg/L. The corresponding COD removal rates were: 1,098, 1,067 and 1,161 g/m²/day. The significant contribution of the passive air pump was well established in nitrification beds, but not in beds with large size gravel (Lahav et al., 2001). In beds with larger gravel size, the smaller surface area can result in limiting biofilm concentrations rather than limiting oxygen conditions, reducing the advantage of the passive pump. Although further investigation is under way, at present it seems that under conditions of high COD and TSS loading rates where larger size media particles have to be used, the passive air pump contribution to the vertical bed performance is insignificant.

The effectiveness of the passive air pump during the rest period

A regeneration period without passive air pump operation was performed after period 4 of “continuous feeding.” No water was recirculated in the bed and the air pipe was left open as well as the drainage valve at the bottom of the bed. The pore space recovered to 60% of its initial value after only 23 days of rest period (Fig. 4, continuous 4), which is probably the result of bed drying accompanied with aeration. In contrast, during rest periods with passive pump operation, a maximal recovery of 55 to 60% was achieved after more than 40 days. Comparing all the rest periods performed with the passive air pump to the one without passive pump operation clearly indicates the advantage of regeneration without the pump.

Sequential PAVB operation

As already mentioned the PAVB in this project was designed as the first semi-intensive treatment stage prior to other extensive technologies (stabilization ponds, constructed wetlands, etc.) targeted at minimizing water loss due to evaporation. The results presented here indicate that the vertical bed removes about 55–65% of the organic load. To improve performance and obtain higher COD removal rates, a number of vertical bed units were operated in series. During the “intermittent feeding” periods of operation, three vertical beds were operated in series (VB1, VB2, and VB3). During “continuous feeding” (period 4), two beds were operated in series (VB1 and VB2). Each additional vertical bed differed in media properties, where gravel size decreased with each sequential bed (6.5 and 3.5 mm for the second and third unit, respectively). COD removal and the corresponding BOD removal in each step are depicted in Fig. 8. Effluent COD concentrations were between 50 and 128 mg/L during the different operational modes and the corresponding BOD concentrations were between 45 mg/L and close to zero. The overall average COD and BOD reductions in the vertical bed system were 83 and 88%, respectively. When COD concentrations were low (VB3), nitrification occurred as well (not shown). On average, influent NH₄⁺-N concentration was 65 mg/L, while in VB3 effluent NO₃⁻-N concentration was 43 mg/L.

CONCLUSIONS

Two modes of PAVB operation were compared: “continuous feeding” until clogging followed by a rest period and “intermittent feeding” with predetermined feeding and rest periods of 8 and 16 h, respectively. The results indicate that “continuous feeding” operation is advantageous over the intermittent operation. Both COD removal rate (800 g/m²/day vs. 400 g/m²/day) and COD removal efficiency (50 vs. 40%) were higher during “continuous feeding.” In contrast to PAVB for tertiary treatment, no significant advantage was shown in using passive aeration when the PAVB was used for secondary treatment with a relatively large particle size (15 mm). Clogging of the bed with apparent ponding occurred at free pore space of 30 to 35% from its initial value. The regeneration rate of bed pore space was faster when no water was recirculated through the bed. Without constant wetting, bed drying accompanied with aeration probably accelerated biomass disintegration and decay. Sequential operation of a number of units with different physical characteristics enabled the achievement of higher effluent qualities and nitrification.

REFERENCES


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