Minimizing land requirement and evaporation in small wastewater treatment systems

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Abstract

Water supplies in the Middle East arid climate are a scarce commodity making treated wastewater an economically attractive source for increasing the limited existing water resources for agricultural purposes. In order to minimize water losses with the corresponding increased salinity and to reduce land demand, an integrated system based mainly on high-rate semi-intensive treatment units is being tested and demonstrated. The units include an upflow anaerobic sludge blanket (UASB) reactor and vertical and horizontal flow wetlands. The units are characterized by simple and low-cost maintenance with minimal energy input. Three years of pilot plant results from the combined system are presented in this paper. The results show a high organic removal rate for the combined system: 140 g COD/m²/day for the scheme, which included a UASB reactor followed by two PA VB units and subsurface horizontal flow CW. Even higher rates of 900 g COD/m²/day were achieved for the same scheme by replacing the final CWL with another PA VB unit. These high rates allow for a small treatment plant footprint equivalent to 0.13–0.9 m² per person, assuming 125 g COD per person per day.

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1. Introduction

Water supplies in the Middle East arid climate are a scarce commodity making treated wastewater an economically attractive source for increasing the limited existing water resources for agricultural purposes. In order to catalyze the implementation of wastewater treatment and to realize the benefits of reuse in rural areas, a collaborative project of Israeli, Palestinian and Egyptian organizations was undertaken, sponsored by the USAID MERC (Middle East Regional Cooperation) program. The project teams are presently investigating appropriate, affordable, safe, and replicable wastewater treatment systems capable of producing high quality water that can be used for irrigation in
intensive sustainable agriculture. At the heart of the project is a demonstration pilot plant focusing on wastewater treatment located in Sakhnin, an Arabic town in Northern Israel, and a pilot plant in El-Sadat, Egypt, concentrating on reuse for irrigation.

Based on land availability, population size, climatic conditions, and socioeconomic considerations in rural Middle East, the appropriate technology should be energy extensive, reliable, simple, low cost, and low impact. However, the classical combination of extensive treatment units (anaerobic ponds-facultative ponds-reservoir) or wetland systems results in substantial water losses and increased salinity due to the high evaporation rates in the semi-arid climate and can also generate environmental nuisances such as malodors and flies. The increase in salinity due to water loss is particularly critical for water reuse in crop irrigation. In Israel, tap water conductivity is typically 1000 µS and after use rises to 1500 to 2000 µS and more in the untreated wastewater. Any further increase in salinity by evaporation during treatment can render the wastewater unusable for many crops. In order to minimize water losses and increased salinity and to reduce land demand while still maintaining the above requirements, an integrated system based mainly on high rate semi-intensive treatment units is being tested and demonstrated for effluent recycling in olive cultivation and for other uses such as river reclamation. The integrated system includes an upflow anaerobic sludge blanket (UASB) reactor unit and two sequential passively aerated vertical bed (PA VB), followed by either horizontal flow constructed wetland or additional PA VB unit. The semi-intensive units (UASB + PA VB) can significantly reduce land requirement by reducing the organic load applied to subsequent extensive polishing unit, resulting in minimal water loss and avoiding high effluent salt concentration. The units are characterized by simple and low cost maintenance with minimal energy input since oxygen supply is not required for the removal of both the organic matter and nitrification. The combination of these two units ensures year round stable effluent quality in the typical Middle-East semi arid climate where most of the year temperatures above 20°C prevail but drop to 10°C and lower in winter. This paper presents 3 years of pilot plant results obtained from the combined system.

2. Materials and methods

2.1. Experimental systems

2.1.1. UASB-RALF type reactor

A modified version of the well known UASB, known by its Portuguese name RALF, with a conical shape and no gas separator was used as a first step treatment unit after primary sedimentation (working volume of 7 m³ and surface area of 8.6 m²). This UASB type was designed, developed and implemented at many sites in Brazil for municipal wastewater treatment (Sandino and Yee-Batista, 2000).

2.1.2. Passively aerated vertical beds (PA VB)

This system consists of a “passive air pump” driven by a fill and draw hydraulic operation cycle (Green et al., 1998). During rapid drainage (the draw phase), each volume of effluent leaving the lower part of the bed is replaced by an equal volume of fresh air supplied by an aeration pipe. The aeration pipe traverses the porous media connecting between the atmosphere and the lower part of the vertical bed and opens only during the draw phase (Fig. 1). At the end of the draw phase, an electrical valve on the top of the aeration pipe closes, trapping oxygen rich air inside the bed. During the fill phase, treated water accumulates in the lower
part of the bed, pushing upwards the ‘trapped’ air from
the draw phase through the bed to the atmosphere. This
allows for good interaction between the oxygen flowing
upwards and the water flowing downwards, maximizing
oxygen transfer and utilization while minimizing
oxygen losses.

Each unit had a height of 2.2 m and a diameter of
2.4 m with an upper surface area of 4.5 m². The units
were filled with two main layers of gravel: the active
upper layer consisting of smaller size gravel (varying
between 15 and 3.5 mm depending on its location in the
sequence) 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. The initial porosity of the unit was 0.48.
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). Three PAVB units were built in the
Sakhnin pilot plant. The units were filled with gravel
whose particles size decreased with each sequential
bed: 15 mm in the first PAVB, 6.5 mm in the second and
3.5 mm for the third unit. The performance of one, two
or three units operating in series was studied. Previous
results showed the importance of passive aeration for
the units containing the two smaller size media units
(6.5 and 3.5 mm) while in the larger size media par-
ticles unit (15 mm) the contribution of the passive air
pump was negligible (Admon et al., 2002).

2.1.3. Constructed wetland (CWL)
A 130 square meter horizontal subsurface flow con-
structed wetland with a width to length ratio of 3:1
and bed depth of 0.6 m was used for polishing pur-
poses. The media used was gravel with a mean diameter
of 1.0 cm and void space of 0.45. The system was
equipped with an adjustable outlet that allowed for
water level control to maintain subsurface flow con-
titions. An impermeable plastic liner was placed at
the bottom of each unit to prevent groundwater con-
tamination. A manifold with drip irrigation outlets was
used for influent distribution. One meter wide inlet and
the outlet zones were prepared with stones (5–10 cm)
larger than the main media. The CWL was planted with
Phragmites australis. During the reported period the
CWL operated at a daily organic loading of about 7.5 g
BOD/m².

2.1.4. Influent wastewater
Wastewater from the Sakhnin town after primary
sedimentation was used as the influent for the treat-
ment system. As is often the case in pilot scale oper-
ation, the control over the influent characteristics was
limited. The result was very large variations in influ-
ent characteristics, both in COD and in suspended
solids concentration. The average influent COD con-
centration was 1050 ± 315 mg/l, varying between 300
and 1700 mg/l. The average influent TSS concentra-
tion was 257 ± 90 mg/l and the average BOD was
562 ± 180 mg/l. The temperature varied from as high
as 30 °C during the summer to as low as 12 °C during
the winter.

3. Results and discussion

3.1. UASB performance
During the first stage of the experiments the per-
formance of the UASB unit as a stand-alone system
was studied. Monthly averages of COD removal effi-
ciencies under conditions of 8h retention time are
presented in Fig. 2. The results show COD removal
efficiencies of about 60% in summer (20–27 °C), and
lower COD removals of between 20 and 40% dur-
ing winter (12–14 °C). The deteriorating effect of low
temperatures on UASB performance is a well known
phenomenon, which limits the implementation of this
technology for domestic wastewater treatment to trop-
ocntries (Lew et al., 2003; Elmitwalli et al., 2001;
Lettinga et al., 1981; Grin et al., 1983; Vieira and Souza,
1986; Seghezzo et al., 2000).

3.2. PAVB performance
The performance of the passively aerated vertical
bed (PAVB) was studied for the two following cases: (1)
pre-settled wastewater as the feeding solution and (2)
UASB effluents as the feeding solution. In both cases
the PAVB was operated continuously (active cycle)
until clogging was observed. A subsequent rest period
was initiated, during which no feeding was supplied
and no water was recirculated through the bed, i.e. no
passive aeration. During the rest period the change in total available pore space was monitored and the subsequent feeding period started only when no further increase in available pore space was observed (Admon et al., 2002).

Table 1 summarizes operational conditions and results from the PA VB operation with pre-settled wastewater (runs 1–3) and UASB winter effluent (run 4) as the feeding solution to the PA VB. The most striking difference is the very long active cycle achieved (85 days) during run 4 as compared to 18–25 days during runs 1–3 operations. This large difference cannot be explained by the two-fold difference in the HLR (9 m/day in runs 1–3 versus 4.5 m/day in run 4). When COD and TSS loading rates were compared, both parameters had the lowest values during run 4 operation (Table 1). The COD loading rate was 2520 g/m²/day during run 4, while during runs 1 and 3 it was two- and three-fold higher (5146 and 7949 g COD/m²/day). On the other hand, during run 2 the COD loading was only 20% higher (3197 g COD/m²/day), yet the time elapsed until clogging was a third than during run 4 operation. The differences in TSS loading rates were much more significant. During run 4, TSS loading rate was 590 g/m²/day while during runs 1, 2 and 3 the loading rates were 2304, 3072 and 3994 g TSS/m²/day (Table 1), respectively, equivalent to four, five and almost eight times the load during run 4. Remarkably, the results show that in spite of the big difference in operational conditions and especially the difference in the active cycle length the total TSS removed in each active cycle (till clogging) was quite similar, between 100 and 180 kg. In contrast, the total COD removed in each active cycle was very different, between 89 and 459 kg COD. Therefore, it seems that the TSS loading rate was the

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Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLR (m/day)</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>4.5</td>
</tr>
<tr>
<td>Days of active treatment</td>
<td>25</td>
<td>27</td>
<td>14</td>
<td>85</td>
</tr>
<tr>
<td>Days of regeneration</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>23</td>
</tr>
<tr>
<td>Influent COD (mg/l)</td>
<td>5146</td>
<td>3197</td>
<td>7949</td>
<td>525</td>
</tr>
<tr>
<td>Influent TSS (mg/l)</td>
<td>240</td>
<td>3072</td>
<td>3994</td>
<td>595</td>
</tr>
<tr>
<td>COD loading rate (g/m²/day)</td>
<td>2304</td>
<td>3072</td>
<td>3994</td>
<td>595</td>
</tr>
<tr>
<td>TSS loading rate (g/m²/day)</td>
<td>579</td>
<td>388</td>
<td>644</td>
<td>964</td>
</tr>
<tr>
<td>Total COD introduced (kg)</td>
<td>259 (165)</td>
<td>373 (190)</td>
<td>323 (224)</td>
<td>295 (171)</td>
</tr>
<tr>
<td>Total TSS (VSS) introduced (kg)</td>
<td>260</td>
<td>76</td>
<td>148</td>
<td>250</td>
</tr>
<tr>
<td>COD removed (mg/l)</td>
<td>832</td>
<td>256</td>
<td>376</td>
<td>944</td>
</tr>
<tr>
<td>TSS (VSS) removed rate (g/m²/day)</td>
<td>281 (NA)</td>
<td>89</td>
<td>115</td>
<td>459</td>
</tr>
<tr>
<td>Total COD removed (kg)</td>
<td>100 (NA)</td>
<td>NA</td>
<td>180 (77)</td>
<td>119 (90)</td>
</tr>
</tbody>
</table>

* Calculated only for the active period, does not include the rest period days.
* Including the active and rest periods.
most influential parameter affecting the rate of bed clogging.

The overall COD removal rate was calculated, taking into account the following rest period for each cycle. The COD removal rates were 832, 256, 376, and 944 g COD/m²/day for runs 1, 2, 3, and 4, respectively. The higher removal rate calculated for run 4 was the result of the high ratio of active to rest periods, made possible by the relatively low TSS loading rate. The low TSS content in run 4 was mainly a result of TSS entrapment in the UASB reactor. The results clearly show the advantage of using UASB effluent as the feed water to the PA VB as opposed to using wastewater after primary sedimentation with high TSS and COD concentrations, typical to rural areas in the Middle East.

3.3. Combined UASB and PA VB performance

In the previous sections, the sensitivity of the UASB unit to lower temperatures and the advantage of using UASB reactor effluent as the feed to the PA VB when treating wastewaters with high TSS and COD concentrations was shown. Based on the results an integrated system consisting of UASB reactor followed by two sequential PA VB and horizontal flow wetland (CWL) was operated in order to achieve required effluent qualities during the whole year. In addition, a second scheme based on the UASB unit and three sequential PA VB with decreasing gravel size (no CWL) was also tested. Similar COD, BOD and TSS results were observed in both schemes of the combined system and the average values for each system component are given in Fig. 3.

Yearly average results showed that the UASB unit removed 50% of the COD, 60% of the BOD, and 52% of the TSS. The first PA VB removed 48, 56, and 40% of the remaining COD, BOD, and the TSS, respectively. The second PA VB subsequently removed 47, 55 and 61% of the COD, BOD and TSS, respectively, remaining in the effluent of the first PA VB. The last unit (either CWL or a third PA VB) removed 32, 76 and 63% of the COD, BOD and TSS, respectively, remaining in the effluent of the second PA VB. The average effluent concentrations of the combined system contained 100 ± 29 mg/l COD, 11 ± 5 mg/l BOD and 11 ± 7 mg/l TSS.

While the organic and TSS removal efficiency were similar in the two schemes of the combined system, the total surface area was very different. In the first scheme (CWL as last stage) the system total area was 150 m² while in the second scheme (three sequential PA VB and no CWL) the total area was only 22.5 m². In both cases the system treated 22 m³/day. It should be emphasized that even the higher surface area in the first scheme is still much smaller than that of classical extensive systems based on ponds and had only minor impact on the resulted water produced (assuming evaporation rates of 5–10 mm/day and the expected water loss is 3–7%).

The ability of the combined system to deal with nitrogen compounds transformations and removal was studied as well. Fig. 4 shows the ammonium and nitrate concentrations in the relevant units for the two schemes of the combined system. Reduction of about 50% in ammonium concentration (from 49 to 24 mg/l as N) due to oxidation to nitrate was observed in the second PA VB as opposed to negligible nitrification in the preceding units. This can be explained by reduced heterotroph competition due to favorable C/N ratio for nitrification. The typical anaerobic conditions prevailing in the sub-surface flow CWL in the first scheme prevented further nitrification in this unit, and facilitated almost complete denitrification. The resulting effluents contained 20 mg/l ammonium and 5 mg/l nitrate. In contrast, in the second scheme, the aerobic conditions in the third PA VB allowed for almost complete ammonium oxidation while no denitrification activity was detected. The resulting effluents contained less than 4 mg/l of ammonium and close to 50 mg/l of nitrate. This alternative can be used when ammonium toxicity and oxygen demand are of major concern. For cases when complete
nitrogen compounds removal is required a subsurface flow CWL unit can be incorporated in the scheme with effluent recirculation.

4. Conclusions

The combined system comprising of semi-intensive treatment units (UASB + PA VB) was found to significantly reduce land requirement, minimize water loss, and avoid increased effluent salt concentration. The units are characterized by simple, low cost operation and maintenance with minimal energy input since oxygen supply is not required for the removal of both organic matter and nitrification. The combination of the different units ensures year-round stable effluent quality in the semi-arid climate typical to the Middle East.

The results show a high organic removal rate for the combined system: 140 g COD/m²/day for the scheme, which included a UASB reactor followed by two PA VB units and subsurface horizontal flow CW. Even higher rates of 900 g COD/m²/day were achieved for the same scheme by replacing the final CWL with another PA VB unit. These high rates allow for a small treatment plant footprint equivalent to 0.13–0.9 m² per person, assuming 125 g COD per person per day.

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