Comparison of bioreactors with different kinds of submerged packed beds for domestic wastewater treatment
P. Mijaylova Nacheva, G. Moeller Chávez, C. Bustos, M. A. Garzón Zúñiga and Y. Hornelas Orozco

ABSTRACT
The performance of aerobic submerged packed bed reactors was studied for the treatment of domestic wastewater using different kinds of packing materials with high specific areas (760–1,200 m²/m³). The tested materials were ceramic spheres, crushed tezontle, grains of high density polyethylene (HDPE), of low density polyethylene (LDPE) and of polypropylene (PP), cubes of polyurethane (PU) and polyethylene tape (SESSIL). The bioreactors were operated in continuous regime, applying organic loads in the range of 0.8–6.0 g COD.m⁻².d⁻¹. The obtained specific COD removal rates were very similar in all the reactors when they were operated at organic loads up to 2.0 g COD.m⁻².d⁻¹, after which differences in effectiveness appeared and the best results were determined in the reactors with SESSIL, LDPE and PU. Very low TSS, O&G and turbidity were obtained in all the effluents. The NH₃⁻N and TN removals were dependant on the dissolved oxygen (DO) concentration and the removals at DO of 5 mg/l were 84–99% and 61–74% respectively. The best removals were determined in the reactors with PU, SESSIL and LDPE. The reactor with tezontle had also a good performance when operated with loads up to 1.0 g TN.m⁻².d⁻¹. The best phosphate removals (38–49%) were obtained in the reactors with PU, tezontle, ceramic sheres and SESSIL.

Key words | aerobic biofilters, submerged bed, wastewater treatment

INTRODUCTION
It has been already demonstrated that aerobic submerged fixed bed bioreactors are an effective option for domestic wastewater treatment (Robinson et al. 1994; Mendoza-Espinoza & Stephenson 1999; Farabegoli et al. 2003). These reactors are able to retain a large biomass quantity which makes them compact and very suitable for small wastewater treatment plants. Compared with other kinds of biofilters, the aerobic submerged fixed bed bioreactors are the most suitable system for treatment of wastewater with a high level of hydraulic flow and organic load variation, which is typical for the small plants (Schlegel & Koester 2007). In addition, several experimental works have shown that the submerged packed bed bioreactors have the capability to simultaneously remove organic matter and nutrients (Meaney & Strickland 1994; Takizawa et al. 1996; Peladan et al. 1996). The shortcoming of these systems is the need to perform periodic washings and flushing with air in order to avoid clogging effects. Plastic media are the most frequently used material for biofilm support in the aerated submerged packed bed reactors. The biofilm carriers are made of polyethylene (PE), polypropylene (PP), polyvinylchloride (PVC) or other synthetic materials, manufactured in the form of blocks of perforated cylindrical tubes or corrugated thin sheets, as well as in the form of loose particles of different shapes. The characteristics of the packed bed materials used determine the structure of the biofilms developed in the reactors, as well...
as the reactor operation mode and the process effectiveness (Hamoda 1989; Moore et al. 2001; Wuertz et al. 2003). The most important media properties are specific bed area, density, surface roughness and porosity, percentage of the bed void spaces and durability, as they influence the process effectiveness. Greater surface area allow larger biomass per unit volume of the reactor, while greater void spaces allow higher oxygen and mass transfer to the biofilm and reduce clogging risks in the fixed bed (Wuertz et al. 2003). Specific surface area densities from 100 to 300 m²/m³ have been proven viable (Wuertz et al. 2003; Schlegel & Koester 2007).

Many new packing materials which allow higher surface densities have already been developed and some of them have been successfully commercialised, while others are still under development and testing. The objective of this work was to compare the performance of seven aerobic submerged fixed bed bioreactors, using packing materials with specific areas in the range of 760–1,200 m²/m³, for their employment in small domestic wastewater treatment plants while considering the requirement of obtaining reclaimed water for reuse.

MATERIALS AND METHODS

Experimental set-up and packing materials

The experimental work was carried using seven acrylic reactors (1.5 m height, 15 cm external diameter and 0.9 m packed bed height, with a volume of 20 l each one), operated in a continuous regime, in downflow mode, with effluent recycling and applying different organic loads in the range of 0.8–6.0 g COD.m⁻².d⁻¹. The schematic diagram of the reactors is presented on Figure 1. Fine bubble aeration was supplemented using porous stone diffusers installed on the bottom of the acrylic columns. The reactors were packed with different support materials, the general views of which are illustrated on the Figure 1. Two natural materials were used: ceramic spheres and previously crushed tezontle (volcanic stone widely available in Mexico). The rest were synthetic materials, three of them were high and low density polyethylene grains, and polypropylene grains (manufactured in Mexico), polyurethane cubes (Germany) and polyethylene tape (SESSIL, Germany). The characteristics of the support materials are presented in Table 1. The granulated materials had effective diameters between 3.0 and 4.5 mm and the polyurethane cubes had 2.5 cm side. The polyethylene tape was 3 cm wide, cut in pieces 15 cm long. The pieces were inserted perpendicularly to a vertical axis made of two braided steel wires, holding them in their centre similarly to a brush. As it can be seen in Table 1, the specific areas of the packed beds were between 760–1,200 m²/m³ and the bed media voidage was between 42.3 and 99%.

Experimental procedure and analysis

The characteristics of the wastewater used as a model, which was an effluent from the primary treatment, are presented in Table 2. The start-up of the biofilters was performed without any special inoculation, only by feeding the wastewater with an organic load of 0.8 g COD.m⁻².d⁻¹. After the biofilm development and the process stabilization, four organic loads were evaluated, each one during four
months. The operational parameters for each experimental stage are presented in Table 3. The recycling flowrate was maintained constant and equal to the influent flowrate during the first two experimental stages and it was increased 50% during the next stages. The dissolved oxygen (DO) concentration during the second, third and fourth experimental stages was varied at two levels, 2 and 5 mg/l, and the duration of each experimental period was of two months. The back washing procedure was established individually for each biofilter depending on the hydrodynamic conditions in the reactors.

The head losses over the filter beds were continuously monitored and backwashing with treated water and/or air flushing was practiced when they reached a maximum level.

The procedure in the biofilters with ceramic spheres and tezontle consisted in simultaneous flushing and water injection in the bottom until a 15–20% bed expansion was reached. In the rest of the reactors only air flushing was practiced when necessary.

The parameters DO, pH and temperature in all the bio-reactors were measured daily. The performance was evaluated based on COD, TSS, NH$_3$-N, TN and PO$_4$-P, which were determined twice a week. The O&G and turbidity were also evaluated in the effluents. The analytical measurements were done according to *Standard Methods for Examination of Water and Wastewater* 1998. Micrographs of samples of the packed beds were obtained using a scanning electron microscope JSM-6400 Noran. Biomass in the reactors was determined in samples taken from three different heights of the reactor packed beds. During the start-up the biofilm was characterized by heterotrophic plate count (HPC), which was performed using the standard spread plate method (APHA 1998). Samples with an area of 2 cm$^2$ were extracted, immersed within sterile water in a vial and sonicated by ultrasonic cleaner for 2 minutes to re-suspend the bacteria colonized on the surfaces of the samples. The re-suspended liquids were analyzed by the method mentioned above, to determine the amount of biofilm heterotrophic bacteria. Plates were incubated for 48 hours at 35°C after which the colony-forming units (CFU) were determined. After the startup period biomass was measured by the dry solids at the end of each experimental

### Table 1 | Characteristics of the materials used in the packed bed reactors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>T</th>
<th>C</th>
<th>SESSIL</th>
<th>PU</th>
<th>HDPE</th>
<th>LDPE</th>
<th>PP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle density, t/m$^3$</td>
<td>1.21</td>
<td>1.33</td>
<td>0.97</td>
<td>0.96</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>Apparent density, t/m$^3$</td>
<td>0.56</td>
<td>0.73</td>
<td>0.11</td>
<td>0.12</td>
<td>0.57</td>
<td>0.54</td>
<td>0.56</td>
</tr>
<tr>
<td>Bed media voidage, %</td>
<td>54.1</td>
<td>45.2</td>
<td>99</td>
<td>99</td>
<td>42.3</td>
<td>44.5</td>
<td>42.8</td>
</tr>
<tr>
<td>Bed pore volume, ml/g</td>
<td>1.53</td>
<td>1.66</td>
<td>1.16</td>
<td>1.20</td>
<td>2.41</td>
<td>2.29</td>
<td>2.38</td>
</tr>
<tr>
<td>Specific bed area, m$^3$/m$^3$</td>
<td>1,210</td>
<td>1,032</td>
<td>1,098</td>
<td>1,102</td>
<td>1,177</td>
<td>755</td>
<td>1,001</td>
</tr>
<tr>
<td>Effective diameter of size, mm</td>
<td>3.25</td>
<td>3.25</td>
<td>30 × 150</td>
<td>25</td>
<td>3.0</td>
<td>4.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Shape</td>
<td>granules</td>
<td>spheres</td>
<td>tapes</td>
<td>cubes</td>
<td>granules</td>
<td>granules</td>
<td>granules</td>
</tr>
</tbody>
</table>

Note: T-Tezontle grains; C-ceramic spheres; SESSIL-Polyethylene tape; PU-polyurethane cubes; HDPE-High density polyethylene grains; LDPE-low density polyethylene grains; PP-polypropylene grains.

*Bio-available area, provided by the manufacturer.

### Table 2 | Wastewater characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD, mg/l</td>
<td>182</td>
<td>100</td>
<td>300</td>
</tr>
<tr>
<td>O&amp;G</td>
<td>11</td>
<td>7</td>
<td>13</td>
</tr>
<tr>
<td>TSS, mg/l</td>
<td>56</td>
<td>41</td>
<td>75</td>
</tr>
<tr>
<td>VSS, mg/l</td>
<td>43</td>
<td>38</td>
<td>56</td>
</tr>
<tr>
<td>Turbidity, NTU</td>
<td>64</td>
<td>25</td>
<td>87</td>
</tr>
<tr>
<td>TKN, mg/l</td>
<td>47</td>
<td>19</td>
<td>60</td>
</tr>
<tr>
<td>NH$_3$-N, mg/l</td>
<td>39</td>
<td>12</td>
<td>45</td>
</tr>
<tr>
<td>Ptotal, mg/l</td>
<td>12</td>
<td>5</td>
<td>18</td>
</tr>
<tr>
<td>Temperature, °C</td>
<td>24</td>
<td>19</td>
<td>30</td>
</tr>
<tr>
<td>pH</td>
<td>7.6</td>
<td>7.1</td>
<td>7.8</td>
</tr>
</tbody>
</table>
The detached biomass accumulated on the bottom was also quantified and purged at the end of each stage.

RESULTS AND DISCUSSION

Start-up and process stabilization

The operation of the seven experimental bio-reactors began with the feeding of the wastewater used as a model, applying an organic load of 0.8 g.m\(^{-2}\).d\(^{-1}\). The amounts of the heterotrophic bacteria in the biofilms formed on the surfaces of the different packing materials are presented in Figure 2a. As in can be seen, the fastest biofilm formation was observed on the surface of the polypropylene (PP) grains, followed by the polyurethane (PU) material, low density polyethylene (LDPE), tezontle (T), ceramic (C) and finally the high density polyethylene (HDPE). After two weeks of operation, the differences in the HPC on the surfaces of the different materials were reduced from 5 to only 2 log CFU/cm\(^2\) and the characterization of the effluents was started. Figure 2b shows that the COD removal increased gradually and the greatest removals were determined in the reactors with SESSIL tape and with LDPE grains. After one month of operation the removals were 92–93% in these reactors, almost 90% in the reactor with tezontle and with PU cubes, whereas the removals were of 78–80% in the reactors with PP and HDPE grains and in the one with ceramic spheres.

There was not correlation between the determined heterotrophic bacteria amounts and the COD removals in the reactors (day 15–30 from the start-up), which means that the differences obtained of the biomass quantity in the biofilters are small and insignificant for the process performance.

Bio-reactor performance at different operational conditions

As there were no statistically significant differences between the COD concentrations obtained during the periods with DO of 2 and 5 mg/l, the averages determined during the entire experimental stages were calculated and presented on Figure 3a. The effluent COD averages were between 22 and 36 mg/l during the first two phases when loads of 0.8 and 2.0 g COD.m\(^{-2}\).d\(^{-1}\) were applied. With the load of 4.0 gDQO.m\(^{-2}\).d\(^{-1}\) the concentration averages were between 37 and 48 mg/l, and with the greatest load between 49 and 59 mg/l. The obtained averages of
the COD removals are presented on Figure 3b. As it can be seen 84 ± 4% COD removals were obtained with loads of 0.8 and 2.0 g COD.m⁻².d⁻¹. When the load of 0.8 g COD.m⁻².d⁻¹ was applied, the highest average removals were determined in the biofilters with PU and SESSIL (87% in both of them), followed by the ones with ceramic spheres, LDPE and tezontle (84, 83 and 82 respectively). The biofilters with PP and HDPE had the lowest averages (81 and 80% respectively). At the load of 2.0 g COD.m⁻².d⁻¹ the performance of the biofilters with SESSIL stayed high but the removal in the reactor with PU decreased to 84%. The biofilter with ceramic spheres conserved the same effectiveness, while the rest of the reactors showed a 2–4% improve. The COD removal determined at the load of 4.0 g COD.m⁻².d⁻¹ diminished in 6–11%. The greatest average (79%) was determined in the biofilter with SESSIL. Almost 78% removal was determined in the reactors with PU, LDPE and tezontle. The rest of the reactors allowed 73–75% COD removals. Another removal decrease (of 5–10%) was observed during the application of the highest load (of 6.0 g COD.m⁻².d⁻¹). At this load, the greatest removal was obtained in the biofilters with SESSIL (73%), followed by the reactor with PU, PP and LDPE (71% in all of them). The averages diminished by 10% in the biofilter with tezontle, as well as in the reactors with HDPE and ceramic materials. The calculated biodegradation rates were very similar in all the reactors during the first two experimental stages (Figure 3c), with a standard deviation of only 0.04–0.05 g COD.m⁻².d⁻¹. The COD removal rates increased with the raise of the organic load, in spite of the removal efficiency decreases. The average COD removal rate for all the reactors was 3.41 g COD.m⁻².d⁻¹ at the organic load of 4.0 g.m⁻².d⁻¹ and 4.59 g COD.m⁻².d⁻¹ at the highest organic load, with a standard deviation of 0.14 g COD.m⁻².d⁻¹.

The evaluation of the effluent TSS concentrations indicated that all the values were smaller than 10 mg/l. However, the average turbidity values were different: 7 NTU in the effluents from the biofilters with PU, tezontle and LDPE, 8 NTU in the effluents from the reactors with SESSIL, 9 NTU in the effluent from the reactor with HDPE, 10 NTU in the one with PP and 22 NTU in the reactor with ceramic spheres. The turbidity was lower than 5 TNU in all the reactors' effluents except the one from the reactor with ceramic spheres during the first two experimental stages. The O&G analysis indicated values lower than 5 mg/l in all the reactors during the entire experimentation time.

Nitrogen and phosphorous removal

The NH₃-N and TN removal rates are presented on Figure 4 as averages for each experimental period. All the reactors showed good NH₃-N removal efficiencies (between 91.2 and 94.5%) with an average removal rate of 0.158 ± 0.002 g.m⁻².d⁻¹ during the operation with the smallest load, in spite of the relatively low DO in the reactors (2 mg/l). At this load, the reactors with PU cubes, tezontle and SESSIL had higher TN removal rates (average of
0.138 g.m$^{-2}$.d$^{-1}$) than those determined in the rest of the reactors (average of 0.126 g.m$^{-2}$.d$^{-1}$). The load increase gave higher removal rates, but the removal efficiencies of the reactors decreased. When the reactors were operated with a load of 0.43 g NH$_3$-N.m$^{-2}$.d$^{-1}$ and DO $= 2$ mg/l, the removal efficiencies were 84.0–91.1% and the removal rates 0.280–0.332 g NH$_3$-N.m$^{-2}$.d$^{-1}$, the higher ones in the biofilter with tezontle and with PU. The TN removals were of 53.4–63.9% with rates of 0.280–0.322 g TN.m$^{-2}$.d$^{-1}$. The operation with the same load, but at DO of 5 mg/l, allowed more than 11% NH$_3$ and TN removal efficiency enhancement. The removal rates were of 0.422 g NH$_3$-N.m$^{-2}$.d$^{-1}$ and 0.368 g TN.m$^{-2}$.d$^{-1}$ (as averages for all the reactors). There were not significant performance differences during the first two experimental stages. The removal efficiencies determined with the next load (0.86 g NH$_3$-N.m$^{-2}$.d$^{-1}$) and DO = 2 mg/l were lower: 67.7–77.7% for NH$_3$-N and 47.3–55.8% for TN with removal rates of 0.580–0.668 g NH$_3$-N.m$^{-2}$.d$^{-1}$ and 0.490–0.570 g TN.m$^{-2}$.d$^{-1}$.

The reactors with PU, SESSIL and LDPE had the best performance at these operation conditions. The DO increase to 5 mg/l allowed an efficiency increase of almost 17% and a 24% removal rate increase in the reactors. The ammonia removal was greatly affected when operating with the highest load and at DO $= 2$ mg/l. The efficiencies were 6.2–72.4% with rates 0.783–0.927 g NH$_3$-N.m$^{-2}$.d$^{-1}$ for NH$_3$-N removal and 45.1–52.9% with rates 0.700–0.820 g TN.m$^{-2}$.d$^{-1}$ for the TN removal. The differences in the reactor performance were very pronounced and the best results were obtained again in the reactors with PU, SESSIL and LDPE. The DO increase to 5 mg/l allowed an efficiency increase of almost 21% and a 31% removal rate augment in the reactors. All the reactors, except the ones with PP, HDPE and ceramic spheres, allowed the obtaining of concentrations lower than 5 NH$_3$-N mg/l and lower than 13.2 mg TN/l in the effluents when operated with DO $= 5$ mg/l.

The average phosphate removals in the biofilters are presented in Table 4. There was no clear correlation with the applied loads, and the standard deviations were high in all the reactors. The reactor with PU had the best performance during all the experimentation with an average of 49.3% removal. The reactors with tezontle and ceramic spheres allowed high phosphate removal (averages of 45.5% and 40.5% respectively), which can be attributed to the more frequent and intense backwashing procedures. The next by performance was the reactor with SESSIL (average of 38.8%) and the removals were between 6 and 24% in the rest of the reactors.

### Table 4 | Phosphate removals

<table>
<thead>
<tr>
<th>Experimental stages</th>
<th>Average PO$_4$-P removal, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T</td>
</tr>
<tr>
<td>1</td>
<td>47.3 ± 3.3</td>
</tr>
<tr>
<td>2</td>
<td>42.5 ± 3.5</td>
</tr>
<tr>
<td>3</td>
<td>49.1 ± 5.2</td>
</tr>
<tr>
<td>4</td>
<td>43.0 ± 5.1</td>
</tr>
</tbody>
</table>

### Attached biomass in the reactors

The attached biomasses developed on the different kinds of support materials are illustrated on Figure 5, almost 30 days after the start-up. The bio-films was already dense and...
covered completely the surfaces of all the materials. Different kinds of microorganisms were observed: bacteria, including many kinds of filaments, heterotrophic and nitrifying bacteria, bacillus, yeast, fungi and some protozoa species. The bioreactor with SESSIL allowed the highest biomass quantity accumulation, followed by the reactor with polyurethane cubes.

The reactors containing tezontle and ceramic spheres required backwashing procedures once each 48 h. The air flushing frequency was lower in the reactors with the grain materials, with PU and SESSIL, once a week. The cell retention times in the reactors were between 10 and 39d, and the highest values were determined in the reactors with SESSIL and polyurethane cubes. The biomass quantity was 35–48 kg/m³ in these reactors, almost four times greater than the average of the rest of the reactors. The packing materials which provide the highest percentage of void spaces in the bed favoured biomass accumulation, allowing the highest cell retention times without any clogging problems in the bed.

CONCLUSIONS

The aerobic submerged packed bed bioreactors with a specific area of 760–1,200 m²/m³, when operated down-flow in a continuous regime, have high biodegradation rates and allow obtaining of reclaimed water for reuse in public services. The determined specific COD removal rates were very similar in all the reactors when they were operated at low organic load, up to 2.0 g COD.m⁻².d⁻¹. The differences in effectiveness appeared when applying greater loads (up to 6 g COD.m⁻².d⁻¹) and the best results were obtained in the reactors with SESSIL, LDPE and PU. The reactor with tezontle had a good performance with loads up to 4 g COD.m⁻².d⁻¹, after which an efficiency decrease was observed. The reactor with PP had one of the best performances during its operation with the greatest load. The ammonia and TN removal depend more heavily on the dissolved oxygen concentration in the reactor than on the applied loads. The effect of the TN load is greater at low oxygen concentration. Ammonia removals were 83.5–99.4% and TN removals were 61.0–74.1% when the dissolved oxygen concentration was 5 mg/l. The best removals were determined in the reactors with PU, SESSIL and LDPE. The reactor with tezontle was again one of the best performing reactors when operated with loads up to 1 g TN.m⁻².d⁻¹. The reactors with PU, tezontle, ceramic spheres and with SESSIL allowed high phosphate removals.

REFERENCES


