Comparison of the treatment performance of bio-substrate based and meadow brown soil based subsurface infiltration systems for domestic wastewater treatment

Ying-Hua Li, Hai-Bo Li, Hong Wang, Xin Wang, Yi Zou and Tie-Heng Sun

ABSTRACT

To foster the practical development of subsurface wastewater infiltration (SWI) systems in China, two systems were implemented on the campus of Shenyang University. The bio-substrate filled SWI (BSWI) and meadow brown soil filled SWI (MSWI) system operated under the same operation mode. According to the 12-month experimental results, the bio-substrate had much higher potential to be a good substrate as compared to the meadow brown soil. The maximum adsorbing capability for \( \text{NH}_4^+ \)-\( N \) of the bio-substrate was 0.724 mg/g, while for the meadow brown soil, the maximum value was 0.471 mg/g. The amounts of nitrifying and denitrifying bacteria of the BSWI were one order of magnitude higher than that for the MSWI. Ammonia, nitrite and nitrate nitrogen concentrations implied nitrification–denitrification process went well in the BSWI. Moreover, the BSWI system maintained efficient pollutants removal, the mean removal efficiencies were 92.3 ± 1.5%, 96.5 ± 3.1%, 90.0 ± 2.1%, 78.6 ± 1.2%, 91.2 ± 1.1% and 99.7 ± 1.0% for COD, BOD\(_5\), \( \text{NH}_4^+ \)-\( N \), TN, TP and SS, respectively. As compared with the MSWI system, pollutant removal efficiencies improved by 26.8 ± 2.3% for \( \text{NH}_4^+ \)-\( N \), 33.8 ± 1.7% for TN, 22.4 ± 1.4% for COD, 26.0 ± 3.5% for BOD\(_5\) and 14.7 ± 2.9% for TP, respectively.

Key words | domestic sewage, matrix, subsurface wastewater infiltration system, treatment efficiency

INTRODUCTION

The increasing water shortage reported over the past decade is caused primarily by a growing population combined with lifestyle changes, especially in urban areas, and changing rainfall patterns (Masi et al. 2010; Lloréns et al. 2011). Taking advantage of alternative water sources is one possible response to the challenges of fresh water demand, water shortages and environmental protection (Kadam et al. 2008).

Some technologies, such as membrane bioreactors (MBR) or sequencing batch reactors (SBR), have demonstrated the capacity to produce high quality treated effluent. However, cost, application to scale and the relatively low public perception may limit their application in small communities especially in rural areas or developing countries (Lloréns et al. 2011). In such communities, simple, low technology and efficient systems, such as subsurface wastewater infiltration (SWI), may be more appropriate. In SWI treatment, wastewater is firstly treated by conventional physicochemical or biological treatment and then allowed to infiltrate through aerated unsaturated zone wherein it gets purified through processes such as filtration, adsorption, chemical reaction and biodegradation (Lowe & Siegrist 2008). Over the past 20 years, SWI systems gained popularity as an effective and low-cost alternative for wastewater treatment, especially for villages and small communities. Investigators have been engaged in researching and developing SWI systems, such as performance evaluation (Siegrist & Boyle 1987), construction styles (Van Cuyk et al. 2001), biofilm properties (Lowe & Siegrist 2008), hydraulic conductivity (Wang et al. 2010), nitrogen and phosphorus removals (Li et al. 2011). Ideally, a SWI system could perform reliably and achieve the desired risk.
management goals over a design life that can be 10–20 years or more (Siegrist et al. 2004). The soil is a critical component which can help ensure excellent treatment performance with limited operation and maintenance requirements at relatively low cost (Van Cuyk et al. 2001). In a typical SWI system in Northeast China, meadow brown soil is the major filtration medium (Zhang et al. 2005). Meadow brown soil based SWI system generally has good phosphorus removal performance. However, the previous studies showed meadow brown soil based SWI treatment could not meet the demand for hydraulic loading rate (HLR) concerning the increased population (Zhang et al. 2005, 2011). The system has NH$_4$-N removal efficiency lower than 60%, resulting from the insufficient oxygen level to the infiltration medium (Zhang et al. 2011).

The main aim of this study was to develop and test, on-site, a new bio-substrate that would improve the nitrogen removal efficiency at a HLR substantially greater than the maximum recommended loading rates for a meadow brown soil filled SWI system.

**MATERIALS AND METHODS**

**Site description**

The SWI system is situated in Shenyang University (East 123°26′50.60″, North 41°49′00.60″), with a design capacity of 750 population equivalent and covers a total area of 600 m$^2$, with two independent cells (meadow brown soil based SWI (MSWI) and bio-substrate based SWI (BSWI)), length × width = 20 × 15 m, respectively. The site has an easterly slope of approximately 5–7%, encouraging the distribution and collection of the wastewater under gravity. The wastewater treatment system consists of one settling tank, one water regulation tank, one MSWI system, one BSWI system, two collection wells and one collection tank (Figure 1(a)).

**System description**

In the MSWI system, the layer was filled with meadow brown soil to a depth of 1.5 m. The BSWI system was similar to the MSWI, except that the BSWI layer was replaced with bio-substrate. A total of five distribution pipes were constructed in both systems with 2.5 m interval arrangement, which operated in parallel, as shown by Figure 1. The distribution pipes were 200 mm in diameter, 0.5 m underneath. Correspondingly, there were four collection pipes, which were also 200 mm in diameter and 1.5 m underneath (Figure 1(b)). Holes of 10 mm diameter were bored at the bottom and top of the distribution and collection pipes at 200 mm intervals, respectively. To avoid clogging of the holes, distribution and collection pipes were installed in gravel beddings (gravel diameter 3–5 cm).

Thirty sampling points (labeled as A1, A2, A3, B1, B2, B3, C1, C2, C3, D1, D2, D3 and E1, E2, E3) were arranged vertical to the middle distribution pipe with intervals of 0.5 m, as shown in Figure 1(b). Therefore, samples from different depths could be sampled from these locations. Experimental results of A1, A2, A3, B1, B2, B3, C1, C2, C3, D1, D2, D3 and E1, E2, E3 were averaged and labeled as A, B, C, D and E, respectively. The differences between sampling positions, for example, A1, A2 and A3 had been discussed in another article (Li et al. 2011). Surface of the SWI systems was planted with rye grass, which was mainly for landscape planting.

**Matrix**

The packed matrix in the BSWI system, namely bio-substrate, was composed of 65% local meadow brown soil, 30% coal slag and 5% dewatered sludge mixed evenly in volume ratio. The meadow brown soil used was collected from the top 20 cm from Shenyang Ecological Station. The coal slag, 4–8 mm in diameter, was purchased from a local market in Shenyang. The activated sludge was obtained from the aeration tanks in Shenyang Northern Municipal Sewage Treatment Plant, air dried after being centrifuged for 15 min at 1,500 rpm, with a grain size of 16 mesh. The matrix components were mixed in a mixing machine four times with 10 min/time to verify the uniformity in composition. The filled matrix of the MSWI system was meadow brown soil, collected from the top 20 cm from Shenyang Ecological Station. The bio-substrate and meadow brown soil were carefully packed, taking the compaction into consideration. The physical properties of the bio-substrate and meadow brown soil are shown in Table 1.

**Experimental operation**

The raw wastewater was delivered from the sewage system using a wet pump and tubing which was 12 m long, intended to prevent freezing during winter months. The influent was a combined wastewater, from toilets, bathrooms, etc. The settling tank effluent passed through a baffle filter into the regulation tank. The operation of the feed pump in the regulation tank was controlled by an electric timer and float switch that ensured the pump was not activated when the
The level of wastewater in the tank was very low. A valve was attached to the pump delivery hose so that the flow entering the MSWI and BSWI systems could be regulated. The flow rate was measured by a flow meter.

This study lasted for 12 months from January to December 2010. During the study period, intermittent operation mode was adopted in both systems. Each cycle of the intermittent operation included a continuous flow period of 24 h (between 8:30 am and 8:30 am the next day), followed by a drying period of 24 h. The actual HLR during continuous flow period was calculated by dividing the volume of wastewater applied by the infiltrative surface area. All 0.125 m$^3$/m$^2$·d design measurements were accurate to ±0.007 m$^3$/m$^2$·d. Primary effluent was taken by disconnecting the delivery hose from the regulation tank and by then turning on the pump to fill a 500 mL container. Effluent samples were taken from the collection wells receiving effluents from MSWI and BSWI systems, respectively.

**Analytical methods**

The water samples were collected once a week, stored at 4 °C and analyzed within 24 h. In other words, 48 composite water samples of raw wastewater, primary effluent and final effluent were gathered. Chemical oxygen demand (COD), total nitrogen (TN), nitrite nitrogen (NO$_2$-N), nitrate nitrogen (NO$_3$-N), ammonia nitrogen (NH$_4$+N), suspended solids (SS), total phosphorus (TP) and total organics (TOC) were analyzed.

### Table 1 | Comparisons of physical characteristics between the bio-substrate and meadow brown soil

<table>
<thead>
<tr>
<th>Items</th>
<th>pH</th>
<th>Total organics (g/kg)</th>
<th>Surface area (m$^2$/kg)</th>
<th>Hydraulic conductivity (cm/s)</th>
<th>Particle size distribution/%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;1 mm</td>
</tr>
<tr>
<td>Meadow brown soil</td>
<td>6.8 ± 0.2</td>
<td>20.3 ± 0.5</td>
<td>159.2 ± 2.7</td>
<td>(8.9 ± 0.2) × 10$^{-5}$</td>
<td>2.0 ± 0.1</td>
</tr>
<tr>
<td>Bio-substrate</td>
<td>7.3 ± 0.2</td>
<td>35.9 ± 0.4</td>
<td>368.0 ± 4.1</td>
<td>(1.1 ± 0.7) × 10$^{-3}$</td>
<td>27.6 ± 1.2</td>
</tr>
</tbody>
</table>
according to the standard methods (APHA 2005). Hydraulic conductivity was measured according to Bumgarner & McCray (2007). Adsorption capability for NH₄⁺-N was estimated using the method Bumgarner & McCray (2007) put forward. The particle size distribution was investigated by high resolution X-ray diffraction. Surface area of the substrate was determined by a specific surface area measuring instrument (F-Sorb 2400, GAPP). Fitting of the experimental data to the isotherm equations was performed by the use of software, Sigma Plot 10.0 (Systat Software, Inc.). Each water sample analysis was performed in triplicate. Samples for nitrifying and denitrifying bacteria analysis were taken with a sampler from positions as shown in Figure 1. The numbers were measured once a month using the most probable number (MPN) calculation method (Bumgarner & McCray 2007).

RESULTS AND DISCUSSION

Comparison of properties for the bio-substrate and meadow brown soil

The comparison of physical properties (Table 1) implied the bio-substrate had much higher potential to be a good substrate as compared to the meadow brown soil.

As NH₄⁺-N is the dominant type of nitrogen in the wastewater, nitrification is a limiting process for nitrogen removal from the system (Pankay et al. 2008). Improving the surface area was an encouraging method to ensure the ammonia nitrogen adsorbing. Secondly, as the influent passes through the matrix, the biomat would attach on the surface of the matrix. As the operation time goes on, soil tends to be choked by the microbial metabolites, which will shorten the lifespan of the systems (Li et al. 2012). Therefore, an appropriate increase in the larger particle size proportion was adopted as a passive method for removing the microbial metabolites and restoring the hydraulic capacity. It is generally accepted that dissolved oxygen (DO) concentrations above 1.5 mg/L are essential for nitrification to occur (Helen & James 2008; Christian & Peter 2011). In the BSWI system, 2.5 ± 0.3 mg/L DO concentration in the effluent was achieved, 1.4 ± 0.2 mg/L higher than that in the MSWI system, which was most likely resulted from the effect of the bio-substrate. This result was consistent with much more nitrifying bacteria detected in the BSWI system. The bio-substrate offered a suitable micro-environment for pollutants removal that protected the micro-organism through the porous walls of bio-substrate, and also provided a good transmission for wastewater during the bio-reaction.

According to the reports, adsorption–nitrification–denitrification is the main path for the nitrogen removal in the subsurface infiltration system (Zhang et al. 2005; Bali et al. 2010). So the adsorption ability for NH₄⁺-N was measured, as shown in Figure 2.

The NH₄⁺-N adsorbed to the substrates drastically increased with the increase of NH₄⁺-N concentration. According to Figure 2, the bio-substrate had much higher NH₄⁺-N adsorption capacity than the meadow brown soil, in accordance with the fact shown in Table 1 that the bio-substrate had higher level of surface area and pH value than meadow brown soil. Based on careful analysis, the maximum adsorbing capability of the bio-substrate was 0.724 mg/g, 0.253 mg/g higher than that of the meadow brown soil. The adsorbed ammonia nitrogen was then easy to be oxidized to nitrate. The surface of the bio-substrate was then released and ready to adsorb NH₄⁺-N again. Therefore, the bio-substrate had much higher potential to be a good substrate as compared to the meadow brown soil in light of NH₄⁺-N adsorption.

Comparison of nitrogen removal bacteria population in MSWI and BSWI system

In both systems, the number of nitrifying bacteria decreased with increasing soil depth. Furthermore, the nearer to the distribution pipe, the higher amount achieved. On the other hand, the quantity of denitrifying bacteria increased with increasing sampling depths. Similar to the nitrifying bacteria, more quantity of denitrifying bacteria achieved nearer the distribution area. According to the reports, nitrification–denitrification process in the SWI system is affected by the...
Substrate. As seen from Table 4, precipitation in the settling tank was relatively more efficient in removing SS than in the MSWI system. During the study period, TN composition in the influent and effluent were analyzed. For the influent, NH₄-N was the main form of TN, accounting for 82.4–85.1%. NO₃-N concentration was 0.2–0.3 mg/L, less than 1% of TN. For the BSWI system, NO₃-N concentration increased to 2.0–2.5 mg/L in the effluent. 29.0–30.5% accounting for TN. On the contrary, NH₄-N concentration declined to 2.3–4.4 mg/L. Zhang et al. (2011) noted that to indicate nitration–denitrification process performed successfully in a SWI system, NO₂-N concentration in the effluent would be between 0.1 and 0.5 mg/L. For the BSWI system, average 0.25 mg/L NO₂-N concentration in the effluent was achieved, which were most likely resulted from the high amounts of nitrifying and denitrifying bacteria. As compared, the value was 0.55 mg/L in the MSWI effluent. The results indicated the nitrification–denitrification process went smoothly in the BSWI system.

Comparison of treatment efficiency of MSWI and BSWI system

During the entire operation period, the characteristics of raw wastewater exhibited both diurnal and seasonal variations due to infiltration to the sewage system especially in wet weather and changes in student populations during weekends and holidays (Table 4). The raw wastewater was pre-treated in a settling tank (hydraulic retention time of 4 h) prior to being discharged into the MSWI and BSWI systems, ensuring the minimization of the clogging risk of pipes and substrate. As seen from Table 4, precipitation in the settling tank was relatively more efficient for the removal of SS than for the other pollutants. Over 77% SS of the influent was removed, but NH₄-N and TN concentrations changed little through this procedure.

During the study period, the pollutant removal performances were measured (Figure 3). As seen from Figure 3, the BSWI system maintained high pollutant removal efficiencies. The annual removals were 92.3 ± 1.5%, 96.5 ± 3.1%, 90.0 ± 2.1%, 78.6 ± 1.2%, 91.2 ± 1.1% and 99.7 ± 1.0% for COD, BOD₅, NH₄-N, TN, TP and SS, respectively.
Table 3 | Treatment performance of subsurface infiltration system

<table>
<thead>
<tr>
<th>Sampling point</th>
<th>Depth (m)</th>
<th>BSWI</th>
<th>MSWI</th>
<th>BSWI</th>
<th>MSWI</th>
<th>BSWI</th>
<th>MSWI</th>
<th>BSWI</th>
<th>MSWI</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.3</td>
<td>(7.0 ± 1.1) x 10^6</td>
<td>(6.6 ± 2.1) x 10^6</td>
<td>(5.4 ± 0.8) x 10^6</td>
<td>(5.2 ± 0.8) x 10^6</td>
<td>(4.9 ± 2.1) x 10^6</td>
<td>(4.6 ± 1.5) x 10^6</td>
<td>(6.8 ± 0.5) x 10^6</td>
<td>(6.6 ± 0.5) x 10^6</td>
</tr>
<tr>
<td>B</td>
<td>0.5</td>
<td>(5.5 ± 0.4) x 10^6</td>
<td>(5.2 ± 0.6) x 10^6</td>
<td>(4.9 ± 0.5) x 10^6</td>
<td>(4.6 ± 0.5) x 10^6</td>
<td>(4.5 ± 0.6) x 10^6</td>
<td>(4.6 ± 0.5) x 10^6</td>
<td>(4.5 ± 0.6) x 10^6</td>
<td>(4.6 ± 0.5) x 10^6</td>
</tr>
<tr>
<td>C</td>
<td>0.7</td>
<td>(5.3 ± 0.5) x 10^6</td>
<td>(5.1 ± 0.3) x 10^6</td>
<td>(4.8 ± 0.6) x 10^6</td>
<td>(4.6 ± 0.6) x 10^6</td>
<td>(4.6 ± 0.6) x 10^6</td>
<td>(4.6 ± 0.6) x 10^6</td>
<td>(4.6 ± 0.6) x 10^6</td>
<td>(4.6 ± 0.6) x 10^6</td>
</tr>
<tr>
<td>D</td>
<td>1.1</td>
<td>(3.8 ± 1.0) x 10^6</td>
<td>(4.1 ± 1.2) x 10^6</td>
<td>(3.9 ± 0.4) x 10^6</td>
<td>(3.9 ± 0.6) x 10^6</td>
<td>(3.9 ± 0.4) x 10^6</td>
<td>(3.9 ± 0.4) x 10^6</td>
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<td>(3.9 ± 0.4) x 10^6</td>
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</table>

Comparing with the MSWI system, there was a dramatic increase for NH₄⁺-N and TN removal efficiencies in the BSWI system, 26.8 ± 2.3 and 33.8 ± 1.7% improved, respectively. At the same time, improvements of 22.4 ± 1.4% for COD, 26.0 ± 3.5% for BOD₅ and 14.7 ± 2.9% for TP were achieved. Due to the uniform operational conditions, the results suggested that it was the bio-substrate that had promoted the pollutant removal performances.

In a SWI system, nitrogen is eliminated mainly through the following three steps (Llorëns et al. 2011). Firstly, ammonifying bacteria transforms organic nitrogen to inorganic nitrogen that mostly contains NH₄⁺-N ions. NH₄⁺-N ions are adsorbed easily by the soil particles which are negative in charge. Secondly, the aerobic oxidation of NH₄⁺-N is first to nitrite, and then to nitrate. Thirdly, in the process of denitrification, nitrate (formed in the nitrification step) is transformed into nitrite under anoxic conditions, then to nitrous oxide, nitric oxide, and finally to gaseous nitrogen. Organic molecules are broken down by the microbiota through fermentation and/or respiration, and mineralized as a source of energy or assimilated into biomass (Beach & McCray 2005). As compared, reports have informed that the removal efficiency for SS has less correlation with microbial activity (Elise et al. 2011). Abiotic processes include precipitation, sedimentation, and sorption maybe particularly important for SS removal (Gilboa et al. 2011). It is therefore speculated that the better performance of pollutants removal in the BSWI system should owe to the sufficient degree of bioprocesses. It could be deduced from Figure 5 that the interaction of purification process and bacteria distribution changed the microbial activities and the volumetric utilization efficiency of the soil beneath the infiltrative surface. These interactions dramatically affected treatment efficiency as they determine the transport and fate of wastewater constituents and the extent of reactions.
that occur in the aqueous or adsorptive phases during infiltration of the influent (Zou et al. 2009). Furthermore, the results of nitrogen species suggested that the effective depth for nitrification was 0.3–0.7 m. Meanwhile, denitrification mainly occurred within the depth of 0.7–1.5 m.

There are reports informed that using a SWI system treating domestic wastewater, the maximum HLR was 0.02 m³/m² d (Jung et al. 2008). Compared with these studies, the hydraulic loading resistance ability of the BSWI system was relatively stronger, due to the usage of the bio-substrate made of activated sludge, brown soil and coal slag. Coal slag, a kind of inorganic waste produced in coal combustion. It had some advantages over other media in supplying microbe abundant inhabitation surface area and possessing strong adsorption capacity (Kadam et al. 2008). The functional sustainability of the infiltration process, both in terms of treatment performance and operational lifetime, was then dependent on the accumulation of biofilms within the void spaces. Furthermore, according to Kizikaya (2008), seeding with activated sludge would produce high biomass concentration. Subsequently one benefit was manifested of a more rapid biofilm establishment using activated sludge and resulting in more rapid increase in COD and NH₄⁺-N removal efficiencies.

CONCLUSIONS

This study demonstrated the performance of full-scale SWI system based on different matrix in treating domestic sewage over a 1 year period. Treatment efficiency of a bio-substrate based system was compared with a meadow brown soil based one.

The result indicated that based on the analysis of physical and biological properties, the bio-substrate provided a more favorable micro-environment for the pollutants removal. For the bio-substrate, the maximum adsorbing capability for NH₄⁺-N was 0.724 mg/g, 0.253 mg/g higher than that of the meadow brown soil. Furthermore, the amounts of nitrifying and denitrifying bacteria in the BSWI system were one order of magnitude higher than that in the MSWI one. In the BSWI system, an annual efficient COD and nitrification reduction was achieved. Furthermore, mean removal efficiencies for TN, BOD₅ and TP were 78.6 ± 1.2%, 96.5 ± 3.1% and 91.2 ± 1.1%, respectively. Compared with the MSWI system, the pollutant removal efficiencies were improved by 26.8 ± 2.3% for NH₄⁺-N, 33.8 ± 1.7% for TN, 22.4 ± 1.4% for COD, 26.0 ± 3.5% for BOD₅ and 14.7 ± 2.9% for TP, respectively. No significant difference was found for SS removal between the MSWI and BSWI systems.

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