Short Communication

Green walls for greywater treatment and recycling in dense urban areas: a case-study in Pune


ABSTRACT

This paper describes a pilot installation of a green wall treating greywater from an office building in Pune, Maharashtra State (NaWaTech project). The pilot installation is located at the main entrance of the state agency responsible for water supply and sanitation. The experimental analysis is in two phases. First phase analysed the results from green walls filled only with LECA® (lightweight expanded clay aggregate). Since results from the first phase were not satisfactory, a second phase was developed. In the second phase, LECA plus sand and LECA plus coconut fibres were tested as porous media in order to increase residence times and consequently green wall treatment performance. The expected improvements in treatment efficiency have been confirmed by the wider range of observed removal rates between Phase I (chemical oxygen demand, COD, 16–20%) and Phase II (i.e. COD removal in the order of 14–86% and 7–80% for LECA-coconut and LECA-sand, respectively), denoting higher treatment potentialities for the new configurations. The obtained effluent quality was fulfilling the Indian law specifications for reuse in irrigation for all the analysed samples, while only the last samples collected during Phase II were showing an appropriate quality for reuse by flushing toilets.

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INTRODUCTION

Adequate water supply in terms of quality and quantity has always been a challenging task for developing cities across the world. The scenario is no different in India, where rapid urbanisation and population growth has increased the stress on water bodies. Across the country there is a strong variation in the water available for users, as ‘class 1’ cities have an average water supply of 80 l/d/PE (Tamil Nadu) to 540 l/d/PE (Chandigarh) (CPCB 2009). This has forced many urban local bodies to develop laws for compulsory recycling and reuse of wastewater. Economic and energy-based analysis of conventional treatment systems clearly indicate the high energy, capital and operation and maintenance demand of these systems while the possible energy generation is quite minimal (Svardal & Kroiss 2011). This is further complicated by the process of building large sewer networks and pumping stations. Hence, for a rapidly urbanising Indian city, building and maintaining such systems becomes a challenging task.

Natural wastewater treatment systems have been proven to be cost effective, efficient and user friendly in many studies. Technologies such as constructed wetlands (CWs), sub-soil filtration and storage and bank filtration, have shown promising capabilities in the treatment of domestic and industrial wastewater (e.g. Vymazal 2011, 2014). Particularly, the potential of natural solutions, such as CWs, for treatment and reuse of wastewater in developing countries has been largely...
accepted (Kivaisi 2001). However, these systems have a much greater land footprint compared with conventional systems.

Principles of source separation of wastewater classify domestic wastewater into blackwater and greywater. Blackwater comprises the discharge from kitchen and toilets, while greywater is low polluted wastewater from bathtubs, showers, hand washing basins and washing machines (Nolde 1999). In residential buildings blackwater generation is generally a low fraction, less than 30% of the total, and even less in non-residential buildings (commercial, offices, etc.) (Li et al. 2009; Scheumann et al. 2009). Hence, greywater treatment can be used for recycling most of the wastewater generated by a closed loop cycle (Dixon et al. 1999).

While many technologies are available for greywater treatment, natural systems like CWs have shown advantages of low energy requirements together with simple and cheap maintenance (e.g. Li et al. 2009; Masi et al. 2010). In the NaWaTech project, many such technologies have been evaluated through pilot and full-scale implementations in urban areas of Pune and Nagpur, two class 1 cities in the state of Maharashtra in India. While root zone treatment systems like CWs for wastewater treatment have shown high potential in rural settlements, the area footprint of these systems has been a bottleneck in mainstreaming them in urban areas where land value is high.

In this specific study, the potential of green walls (also called vertical gardens) has been explored as a viable greywater treatment system that can greatly minimise the treatment footprint and provide a series of benefits in the urban landscape such as greening, CO₂ trapping, O₂ production, microclimate effects, house insulation, etc. (Francis & Lorimer 2011). If the concept of recycling greywater at building or block level could be applied on a large scale in a city, this approach could significantly reduce the dependence on very expensive infrastructures like sewer systems and end-of-pipe large wastewater treatment plants, optimising – by effective decentralised treatment – the overall wastewater management and operative conditions for the treatment itself. Urban development strategy planners could therefore make use of different values for the usual pro-capita parameters when designing lighter sewer networks, and optimise treatment units better if they were focused on the recovery of resources conveyed by the black water fraction.

**MATERIALS AND METHODS**

The experimental set up was constructed on the front walls of the of the office of Maharashtra Jeevan Pradhikaran (the Water Supply & Sanitation Department of Maharashtra state) situated in Pune (Figure 1). The office houses 125 fixed staff and has an average daily visitor count of 65. Dual plumbing was installed in the first and second floors of the building, which connects approximately 60 staff and 25 visitors to a storage tank of 300 L capacity. The pilot green wall comprises two parallel units on either side of the entrance. The inflow from the collection tank is stored in two intermittent loading tanks of 100 L capacity each, whose outflows are controlled by a timer based solenoid valve. The feeding of the treatment unit happens through an hourly flush of 10 L of greywater. The discharge is directly allowed to flow into the garden next to the walls.

Each individual treatment unit consist of a 12 × 6 matrix of pots (6 pots in a column and 12 pots in a row). Each pot has a top surface of 0.01 m². The pots have been planted with the following genus: *Abelia*, *Wedelia Portulaca*, *Alternenthera*, *Duranta* and *Hemigraphis*. A perforated pipe is used for loading the first row of pots. The water flow is then divided along the columns of the matrix arrangement and is collected at the bottom by a drain pipe (Figure 2).

The experimental analysis has been divided in to two phases. Initially, the pots have been filled with an inert planting material – LECA® (light expanded clay aggregates) – to ensure that the only nutrient source for the plants is the greywater. In this first phase, samples of the inlet and outlet were collected weekly and analysed in terms of organic content (biochemical oxygen demand, BOD₅, and chemical oxygen demand, COD). Since results were not satisfactory enough, this phase was ended (lasting from 12th of February to 27th of April 2015) and a second experimental phase was started (from 30th of April to 5th of October 2015). In the second phase the LECA (Ø4–10 mm) was mixed with two other media (sand and coconut fibres) for the two different pilot green wall units in a proportion of 50–50%. The aim of the second phase was to slow the water flow, increase residence time and favour a greater biofilm development. Coconut shell has been adopted due to its high local
availability in India and the lower cost and weight compared with sand. During the green wall’s lifespan, the coconut is expected to disappear due to degradation, but slowly enough (high proportion of lignin based compounds) to allow a full development of plant roots, which would guarantee proper green wall functioning. Samples for the analysis of suspended solids (SS), BOD₅, COD, NH₄⁺-N, and total Kjeldahl nitrogen (TKN) have been collected during the second phase. The results of the first phase are hereby reported as well as preliminary results of the second phase.

RESULTS

The pilot system was put into operation at the beginning of February 2015. The greywater produced by the office...
building is quite light in terms of concentrations, with BOD$_5$ and COD in the ranges of 6–47 mg/L and 20–100 mg/L, respectively, and with average values almost equal to 25 mg/L and 60 mg/L, respectively. The hydraulic loading rate (HLR) and the organic loading rate resulted in 1,000 L.m$^{-2}$.d$^{-1}$ and 167 g.m$^{-2}$.d$^{-1}$, respectively, for the first line, and 96 L.m$^{-2}$.d$^{-1}$ and 10 g.m$^{-2}$.d$^{-1}$, respectively, for all infiltration areas. The maximum HLR for treatment of black water with vertical subsurface flow CWs is equal to 50 L.m$^{-2}$.d$^{-1}$ in summer (DWA 2006); this value can be considered in accordance with the HLR of the all infiltration area for the green wall, which treats wastewater with a lower pollutant load (greywater) compared to the black water. The average BOD$_5$/COD ratio is equal to 0.43. The low contamination with organic matter compared to typical greywater can be explained by the fact that only greywater from hand washing basins is collected in this particular situation. The usually stronger contaminated greywater fractions, i.e. from kitchens and washing machines, are not present in the MJP office buildings.

Influent and effluent concentrations for the two experimental phases are shown in Table 1. During the first phase, the system has shown a low average organic removal efficiency of 18.3% and 24.6% for COD and BOD$_5$, respectively (Table 2). These results suggest a scarce biofilm development, with removal mainly driven by the filtration process only, and a relatively fast percolation of the water throughout the LECA layer that does not allow for an appropriate contact time between the solution and the active agents involved in processes such as adsorption and biosorption. The top layer in the pots was, in Phase I, still completely unclogged and the biofilm was starting to develop. These results could also be explained by a concentration effect created by the evaporation and evapotranspiration of the water from inside the pots. The slow biomass growth can also be justified by the very low content of nutrients (C, N, P) in the inlet.

The unit filled with mixed LECA and coconut fibres has shown a release of carbon generated by the more biodegradable fraction of the coconut fibres up to the 19th of June, with fluctuating influent and effluent concentrations for all the parameters. At the end of this start-up period, a proper biofilm seemed to develop, since the COD, BOD$_5$, NH$_4^+$-N, and TKN effluent concentrations always resulted lower than the influent ones in the subsequent samples up to the end of the second phase. Regarding the unit filled with LECA and sand, interesting removal efficiencies have been observed for all the studied parameters, with higher performances for COD, BOD$_5$, and NH$_4^+$-N when compared

### Table 1 | Influent and effluent concentrations from the two experimental phases

<table>
<thead>
<tr>
<th></th>
<th>Phase I LECA</th>
<th></th>
<th>Phase II LECA-Coconut$^a$</th>
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<th>Phase II LECA-Sand$^b$</th>
<th></th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Influent (mg/l)</td>
<td>Effluent (mg/l)</td>
<td>Influent (mg/l)</td>
<td>Effluent (mg/l)</td>
<td>Influent (mg/l)</td>
<td>Effluent (mg/l)</td>
</tr>
<tr>
<td>COD</td>
<td>84.9 ± 2.5</td>
<td>69.4 ± 1.7</td>
<td>48.8 ± 2.46</td>
<td>21.4 ± 15.3</td>
<td>43.9 ± 22.6</td>
<td>27.7 ± 21.2</td>
</tr>
<tr>
<td>BOD$_5$</td>
<td>39.7 ± 3.2</td>
<td>29.9 ± 2.5</td>
<td>17.1 ± 7.9</td>
<td>6.7 ± 2.7</td>
<td>18.6 ± 10.2</td>
<td>11.0 ± 8.3</td>
</tr>
<tr>
<td>NH$_4^+$-N</td>
<td>–</td>
<td>–</td>
<td>3.4 ± 1.7</td>
<td>1.7 ± 0.7</td>
<td>3.5 ± 0.8</td>
<td>1.1 ± 0.5</td>
</tr>
<tr>
<td>TKN</td>
<td>–</td>
<td>–</td>
<td>4.6 ± 0.8</td>
<td>3.5 ± 3.4</td>
<td>4.6 ± 1.2</td>
<td>3.9 ± 3.0</td>
</tr>
<tr>
<td>SS</td>
<td>–</td>
<td>–</td>
<td>58.8 ± 12.9</td>
<td>45.6 ± 20.0</td>
<td>53.8 ± 18.4</td>
<td>48.1 ± 20.1</td>
</tr>
<tr>
<td>n samples</td>
<td>14</td>
<td>11-12</td>
<td></td>
<td></td>
<td>14</td>
<td>15</td>
</tr>
</tbody>
</table>

$^a$From 19th of June (only after the end of the coconut fibres’ organic fraction release).

$^b$From 30th of April (all samples for LECA-sand greywall in Phase II).

### Table 2 | COD and BOD$_5$ removal efficiency statistics for the two experimental phases

<table>
<thead>
<tr>
<th></th>
<th>COD removal efficiency</th>
<th>BOD$_5$ removal efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phase I LECA (%)</td>
<td>Phase II LECA-Coconut$^a$ (%)</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>Std</td>
</tr>
<tr>
<td></td>
<td>18.3</td>
<td>1.1</td>
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<tr>
<td></td>
<td>53.3</td>
<td>21.3</td>
</tr>
<tr>
<td></td>
<td>42.0</td>
<td>25.8</td>
</tr>
<tr>
<td></td>
<td>24.6</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>53.7</td>
<td>22.0</td>
</tr>
<tr>
<td></td>
<td>44.3</td>
<td>26.1</td>
</tr>
</tbody>
</table>

$^a$From 19th of June (only after the end of the coconut fibres’ organic fraction release).

$^b$From 30th of April (all samples for LECA-sand greywall in Phase II).
with SS and TKN. Coconut fibres seem to perform better than sand and this aspect can be related to the longer retention time provided by the adoption of this filling material in the pots: a complete fill and drain cycle has a duration of 12 minutes in the LECA-sand unit, while this increases to about 40 minutes in the LECA-cocopeat unit.

The statistical analysis of COD and BOD$_5$ removal efficiencies for the two different phases is reported in Table 2. This comparison confirms the improvement of the performances driven by the changes adopted in the second phase. Indeed, COD average removal efficiency is increased from 18.3% in the first phase to 53.5% and 42.0% for LECA-coconut and LECA-sand units, respectively. Similar improvements have been registered also for BOD$_5$ removal. Note that only samples after the end of the coconut organic fraction release (i.e. after the 19th of June) have been used here in the analysis related to the LECA-coconut green wall.

Improvements are also confirmed by the wider range of observed removal efficiencies of single samples between Phase I (i.e. COD removal of 16–20%) and Phase II (i.e. COD removal in the order of 14–86% and 7–80% for LECA-coconut and LECA-sand, respectively), denoting higher treatment potentialities for the new configurations. Higher and more stable removal efficiencies are expected with the increase of plants rooting and the growth of the biofilm.

**CONCLUSIONS**

One common situation of dense urbanised areas in developing countries is the lack of proper treatment for domestic wastewater. This is due both to the common lack of classical centralised treatment (e.g. activated sludge) due to high construction and management costs, and to the scarce availability of area to adopt natural treatment solutions. At the same time, fast developing urban areas are facing a scarcity of high quality water sources for increasing urban water demand. The solution proposed here, the green wall for greywater treatment and reuse, has the potential to respond to these issues with a single simple solution. Namely, the adoption of a low cost natural treatment for dense urbanized areas, which have a high availability of vertical concrete surfaces common in developing country urban centres, thereby resulting in recovery of a huge amount of treated greywater (100 l/PE/d, up to 70–75% of the total daily domestic wastewater) as a new resource for activities requiring water of lower quality (e.g., WC flushing, irrigation) in areas facing increasing water demand. Moreover, green walls are already adopted principally for aesthetic reasons, but also for different ancillary benefits such as air filtration (O$_2$ production and carbon storage), thermal insulation of buildings, and reduction of noise pollution. Consequently, greywater treatment and reuse could be a very promising additional service provided by green walls.

The results exposed in this work highlight that the current set up of the tested green wall could be ready to upscale and be adopted in real cases. Indeed, the effluent quality was, in all samples, already suitable for reuse by land irrigation according to the Indian regional and national regulations; in the last samples collected in Phase II the effluent reached an appropriate quality for reuse by flushing toilets (considering in the treatment scheme a further disinfection by an UV lamp).

**ACKNOWLEDGEMENTS**

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