Pilot-scale evaluation of green roofs with Sargassum biomass as an additive to improve runoff quality

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A B S T R A C T

Green roofs have the potential to be used as a pollutant-sink in urban environments. Unfortunately, until now no systematic study has been conducted to enhance the runoff quality from green roofs. The present work investigates the viability of using low-cost aggregates along with a biosorbent (Sargassum biomass) to prepare substrate mix for extensive green roofs to improve runoff quality. We have used (on a volume basis) 30% perlite, 20% vermiculite, 10% sand, 20% crushed brick, 10% coco-peat and 10% Sargassum biomass to prepare green roof substrate. The developed green roof substrate was found to have low bulk density (487 kg/m$^3$), high water retention capacity (58.5%), air filled porosity (19.5%), and hydraulic conductivity (4195 mm/h). Through laboratory packed column study, we identified superior sorption capacity of green roof substrate towards various metal ions such as Al, Fe, Cr, Cu, Ni, Zn, Cd and Pb. Rooftop experiments in pilot-scale green roof assemblies with Portulaca grandiflora as vegetation were conducted for several artificial rain events (unspiked and metal-spiked). Results based on unspiked artificial rain events suggested that concentrations of most of the chemical components in runoff were highest during the beginning of rain events and thereafter subsided during the subsequent rain events. Metal-spiked artificial rain events revealed that green roofs acted as a sink for various metal ions and generated better runoff, whose quality was significantly less than fresh water standards. Green roofs also showed the potential to neutralize the acidic nature of inlet water and delay runoff generation. Significant differences were also observed between non-vegetated and vegetated green roof assemblies in runoff quality and quantity, with the latter producing better results.

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1. Introduction

Green (vegetated or living) roofs are growing in popularity around the world owing to their unique environmental and social benefits. Green roofs integrate vegetation with undereutilized urban buildings thereby lessening several negative effects of buildings on local ecosystems. They can reduce buildings’ energy consumption and mitigate storm-water runoff thereby reducing flash flood. The addition of vegetation and soil to urban buildings are known to increase sound insulation, and improve fire resistance and the longevity of roof membrane (Oberndorfer et al., 2007; Rowe, 2011). Other potential benefits include air quality improvement, reduction of urban heat-island effect, improvement in the efficiency of solar panels and providing urban environments with more green space (Chemisana and Lamnatou, 2014).

Green roofs are usually comprised of following layers: vegetation, substrate, filter, drainage, root barrier and waterproofing layer (Fig. 1a). The type of each of these layers depends on the type of green roof itself (extensive or intensive). In general, extensive green roofs (thin substrate layer, light weight, drought tolerant plants and low maintenance) are more common than intensive green roofs (thick substrate layer, larger weight, wide variety of garden plants and high maintenance). For extensive green roofs, drought tolerant plants such as sedum are generally preferred; however in some cases grasses, herbaceous perennials and annuals are used (Rowe, 2011). In the case of substrate, wide variety of light-weight inorganic materials such as crushed concrete, expanded slate, expanded clay, crushed brick, volcanic pumice, scoria and sand are used (Nagase and Dunnett, 2011). Usually, green roof substrate is prepared by mixing several inorganic materials to achieve desirable characteristics along with minimal organic matter, such as green waste compost and mulch. As a filter layer, polypropylene or polyester geotextile membranes are usually employed (Pérez et al., 2012). These retain the substrate component, but allow water to pass through the drainage element.
There are two types of drainage systems usually employed in commercial green roof systems viz., plastic drainage modules and light-weight drainage granules (light-weight expanded clay aggregates). Drainage modules are widely used in medium and large scale green roofs, whereas light-weight granules are suitable for small scale systems due to their simplicity, however, in some cases it may be all that is necessary to lift the main substrate above the draining water.

Recent green roof research has focused on plant selection to promote biodiversity (Cook-Patton and Bauerle, 2012), thermal benefits including reduction in urban heat island effect (Kolokotsa et al., 2013), and hydrological properties, in particular, attenuation and retention of stormwater by green roofs (Berndtsson, 2010). Furthermore, the role of green roofs in air purification (Yang et al., 2008), sound insulation (Renterghem and Botteldooren, 2011), aesthetics (Jungels et al., 2013) and roof protection (Rowe, 2011) has been explored. An important factor which is often overlooked in previous studies published in the literature is the runoff quality from green roofs (Berndtsson et al., 2006, 2009). Although without adequate evidence, it is often assumed that green roofs improve the runoff water quality compared to hard roofs (Berndtsson et al., 2009). However, green roofs can also potentially contribute to the degradation of the quality of receiving waters with pollutants released from soil, plants and fertilizers (Vijayaraghavan et al., 2012). Of the very limited literature on runoff quality assessment, green roofs are generally regarded as a source of contaminants (Moran et al., 2003; Berndtsson et al., 2006; Berndtsson, 2010; Vijayaraghavan et al., 2012). The presence of vegetation and growth substrate potentially contributes to pollutants released into water. However, not much effort has been made to improve the quality of runoffs generated by green roofs.

Seaweeds have recently been identified as excellent sorbents for various organic and inorganic contaminants (Romera et al., 2006; Vijayaraghavan and Yun, 2008). In particular, the brown seaweed Sargassum species have shown potential to continuously sorb and immobilize various pollutants (Vijayaraghavan et al., 2009). Furthermore, seaweeds are rich in minerals and nutrients that are important for plant growth. Hence, seaweeds as an additive in green roof substrate have the potential to improve the quality of runoffs and support plant growth. Therefore, the objective of this paper is to explore the possibility of seaweed-based sorbent in growth substrate to improve the quality of green roof runoff. To our knowledge, till date, no study has been conducted on the possibility of an additive to enhance the sorption capacity of green roof substrate. Rainfall simulations on various pilot-scale green roof assemblies were used to evaluate the runoff quality based on various physico-chemical parameters.

2. Materials and methods

2.1. Study site and design of green roofs

The rooftop of Mechanical Sciences Block (IIT Madras, India) was used to conduct green roof experiments from June to September 2013. Several green roof assemblies were custom-designed (50 cm × 50 cm × 25 cm glass assemblies) (Fig. 1b and c), with the same principle as full-scale vegetated roofs. All assemblies were placed on a 4% slope to replicate general roof design. The runoff was collected in a measuring beaker through the opening at the bottom of the assembly. Generally, each assembly consist of three components, an uppermost layer (10 cm thick growing substrate to support plant growth), an intermediate layer
(geotextile filter fabric, which prevent fine substrate particles from uppermost layer from being washed into the drainage layer or out of the system) and a bottom layer (drainage module, a commercial drainage element (flexible drain cell, Bioremegree Technology Solutions, India)). The flexible drain cell is designed to store up to 2 L of water/m² to supply plants during dry periods; whereas the excess water can be drained off. In one assembly, vegetation (*P. grandiflora*) was planted.

2.2. Substrate preparation and analysis

Our previous preliminary study (Vijayaraghavan and Raja, 2014) indicated that the green roof substrate prepared using vermiculite, perlite, sand, crushed brick and coco-peat resulted in maximum plant growth as well as found to comprise of low bulk density (431 kg/m³), high water retention capacity (39.4%) and air filled porosity (19.5%). However, the sorption capacity of above green roof substrate was limited. Thus, in the present study, the organic content (coco-peat) was replaced with equal volume mix of *Sargassum wightii* and coco-peat. The green roof growth substrate comprises of (on volume basis) 20% vermiculite, 30% perlite, 10% sand, 20% crushed brick, 10% coco-peat and 10% *S. wightii*. Exfoliated vermiculite (0.5–2 mm) was procured from Shirama-maruti Vermiculite Mines (Chennai, India), whereas perlite (0.25–1 mm) was purchased from Keltech Energies Ltd. (Bangalore, India). Other inorganic constituents (sand (0.25–1 mm) and crushed brick (4–10 mm)) were obtained from commercial shops. Samples of *S. wightii* were collected from the Mandapam (9°16′47″N 79°7′12″E) region of Tamil Nadu, India. Coco-peat samples were collected from a local nursery. Both organic constituents were dried under sunlight for three days and then further dried in the oven at 60 °C for 24 h. The samples were then grounded and subsequently sieved to obtain average particle sizes in the range of 0.5–1 mm. The physical and chemical characteristics of green roof substrate are discussed in Section 3.1. The bulk density was calculated as the ratio of the dry mass (dried at 105 °C) to the volume of the undisturbed sample. Bulk density (at maximum water holding capacity) was measured as per FLL guidelines (FLL, 2002). Hydraulic conductivity was determined through constant-head or falling-head tests depending on the substrate size (Budhu, 2007). The water holding capacity (WHC) and air filled porosity (AFP) were determined according to the Australian Standard Methods for potting mixes (Standards Australia, 2003).

2.3. Column experiments

Continuous-flow fixed-bed column experiments were conducted to examine the leaching characteristics and adsorption capacity of green roof substrate. A glass column (height = 35 cm; internal diameter = 2 cm) was designed. Around 38.8 g of green roof substrate was packed within the column to yield a bed height of 25 cm. At the top of the column, a layer (3 cm) of glass beads was placed to distribute the inlet water uniformly. The influent (metal-spiked utility water) was pumped downwards through the column using a peristaltic pump at a flow rate of 0.3 L/h. Samples were collected at the bottom of the column at different time intervals and analyzed subsequently for several physico-chemical parameters. Metal-spiked utility (tap) water was prepared by artificial addition of metal ions by mixing their respective nitrate salts in utility water. To decide the concentration to be spiked, metal ions were classified into four groups: non-toxic (Na, K, Mg and Ca), mild-toxic (Fe and Al), toxic (Cr, Cu, Zn and Ni) and highly-toxic (Cd and Pb) metals. In the spiked-utility water, the concentrations were in the order of approximately 0.5, 1, 5 and 10 mg/L for each of highly-toxic, toxic, mild-toxic and non-toxic metal ions, respectively (Vijayaraghavan and Raja, 2014).

Column effluent samples were immediately analysed for pH, conductivity and total dissolved solids. For the analysis of metals (Na, K, Ca, Mg, Al, Fe, Cr, Cu, Cd, Ni, Pb and Zn), the samples were first filtered through a 0.45 μm PTFE membrane filter and then analyzed using inductively coupled plasma-optical emission spectrometry (ICP-OES, PerkinElmer Optima 5300 DV).

2.4. Green roof vegetation

A succulent local species, *P. grandiflora*, was used as a model green roof plant. The species is known for its ability to withstand drought conditions, require less maintenance, provide good ground coverage, ability of rapid multiplication, and have short and soft roots (DDC, 2007). It is commonly known as moss rose and can be easily grown in poor to average, dry to moderately moist and well-drained soils in full sun. This annual is a succulent that typically grows to 6–8 inches tall and spreads to 12 inch or more. Even though *P. grandiflora* is well established in several countries, it was never examined as green roof vegetation. One-month old cuttings of *P. grandiflora* grown in commercial garden soil were obtained from a local nursery. The roots of each cutting were then washed carefully with utility water to minimize the influence of garden soil on green roof substrate. The plants were then planted in the substrate at a density of 64 plugs/m². For the purpose of adaptation, water (0.2 L) was sprayed every two days. In order to protect experimental setup during rain events, a small-ten-like structure was constructed during the course of experiments. Field experiments were started after one month of plant adaptation.

2.5. Rainfall simulation experiments

To investigate the influence of green roof components on runoff water quality changes, rain simulations with local tap (utility) water were conducted on green roof assemblies. Two green roof pilot-scale assemblies were employed in the present experiments. The first assembly (GA-1) consist of drainage element, geotextile membrane and green roof substrate; whereas the second (GA-2) comprise of drainage element, geotextile membrane and green roof substrate planted with *P. grandiflora*. Since the volume of water necessary for experiments was more than 100 L, the simulation experiments were carried out with local tap water. Rain events (5–70 mm) were simulated manually with a sprinkler equally on two assemblies. In total, 10 events were considered with one event amounts to 5 mm (Vijayaraghavan et al., 2012). At the start of each event, 5 mm of utility water was sprinkled at the top of each assembly. The runoff generated was collected at the exit using clean plastic cans. Once there was no sign of runoff, the assembly was left undisturbed for 1 h before further experimentation. Runoff samples from each rain event were analyzed for light metals, heavy metals, and other physico-chemical parameters. In the next set of experiments, the retention capacity of green roof assemblies was examined. For this purpose, simulated rain events were conducted using metal-spiked tap water and the experimental procedure was same as that of un-spiked rainfall events.

3. Results and discussion

3.1. Green roof substrate characteristics

Table 1 depicts the characteristics of green roof substrate employed in the present study. The growth substrate is crucial for success of green roofs as it need to supply nutrients and provide good anchorage for plants. Some of the other important characteristics of green roof substrate include, low bulk density, high water
holding capacity, minimum leaching, high air-filled porosity, high hydraulic conductivity, and minimal organic content. This is generally achieved by mixing materials of different characteristics at defined ratios. In the present study, four different inorganic (perlite, vermiculite, sand and crushed brick) and two different organic (coco-peat and *S. wightii*) materials were employed. The main benefits of using organic matter (coco-peat) are that it maintains good soil structure, increases cation exchange capacity, improves water retention, and supply of nitrogen, phosphorous, potassium and sulfur to plants. In the case of *S. wightii*, it was expected to improve the sorption capacity and stability of green roof substrate in addition to supply of nutrients to plants. It should also be noted that the usage of organic component in green roofs should be limited because too much organic matter might cause shrinkage of the vegetation support course, promote growth of unnecessary weeds, and endanger the long term success of the whole roof. The recommended organic matter in extensive green roofs lies in the range of 0–20% (Torderlund, 2010). Thus, in the present study, organic constitution of final green roof substrate was always equal to 20%. The constituents used in the present study to prepare green roof substrate were of different sizes, which was intentional to alter the volume of air and water held by the final green roof substrate. The dry bulk density was recorded low (487 kg/m³) as compared to other green roof substrates reported elsewhere (Nagase and Dunnett, 2011; Farrell et al., 2013). However, significantly high moist bulk density (at maximum water holding capacity) was obtained (Table 1), which directly indicates the potential of green roof substrate to hold water thereby reduce the runoff volume and supply stored water to plants during dry periods. Similarly, WHC also recorded high value due to the presence of vermiculite (WHC = 62.5%), *Sargassum* (260%) and coco-peat (46.3%). Due to the presence of perlite and crushed brick, AFP was determined to be 19.5%. Perlite is a glassy volcanic rock with a rhyolitic composition, recently has become an important soilless growth medium and also widely used in potting mixes. It provides good aeration and optimum moisture retention for superior plant growth (Gül et al., 2005; Silber et al., 2010). Hydraulic conductivity was estimated to be 4195 mm/h. High values of hydraulic conductivity is preferable to avoid water ponding on the surface of the substrate, which add weight that may overload a structure or run laterally and erode the substrate from the roof. The presence of crushed brick (14,200 mm/h) significantly improved hydraulic conductivity of green roof substrate, whereas perlite (580 mm/h) and *Sargassum* (340 mm/h) severely decreased the hydraulic conductivity. Considering the German FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V.) guidelines for green roofs (FLL, 2002), the observed physical parameters for the prepared green roof substrate were well above the minimum requirements for a green roof substrate (Table 1), which listed the ideal substrate (extensive green roofs) should have WHC (>20%), AFP (>10%), and hydraulic conductivity (>3600 mm/h).

### Table 1
The characteristics of green roof substrate.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Green roof substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size (mm)</td>
<td>0.25–4</td>
</tr>
<tr>
<td>Dry bulk density (kg/m³)</td>
<td>487</td>
</tr>
<tr>
<td>Bulk density (at maximum water) (kg/m³)</td>
<td>1135</td>
</tr>
<tr>
<td>Water holding capacity (%)</td>
<td>58.5</td>
</tr>
<tr>
<td>Air filled porosity (%)</td>
<td>19.5</td>
</tr>
<tr>
<td>Hydraulic conductivity (mm/h)</td>
<td>4195</td>
</tr>
<tr>
<td>pH</td>
<td>8.3</td>
</tr>
<tr>
<td>Conductivity (μS/cm)</td>
<td>210.4</td>
</tr>
<tr>
<td>Total dissolved solids (mg/L)</td>
<td>121.6</td>
</tr>
</tbody>
</table>

### 3.2. Sorption capacity of green roof substrate

In an effort to determine the sorption capacity of green roof substrate, packed column experiments were conducted. Metal-spiked utility water (pH 5.1) was used as influent at 0.3 L/h in a green roof substrate loaded-down flow packed column to examine the sorption/leaching characteristics. Breakthrough curves (outlet concentration/inlet concentration vs. time) along with profiles of other physico-chemical parameters are illustrated in Fig. 2. Important column parameters including the column uptake capacity and % metal removal during entire column operation are presented in Table 2. Considering that several metal ions of varied concentrations were present in the influent spiked water, we fixed the column breakthrough at the point at which any of the outlet metal ion concentration exceeded 0.1 times of its initial concentration.

Green roof substrate-loaded packed column showed good sorption capacity towards all heavy metal ions (Fig. 2). Taking into account the total operation time of 600 min (38 bed volumes or 3 L of spiked-water treated), the column was able to retain all heavy metal ions with the outlet concentration reaching only 0.1 times of the inlet concentration except Ni. For several metal ions including Pb, Cd, Cr and Cu, the green roof substrate displayed total removal efficiencies greater than 99%. For other metal ions such as Al, Fe and Zn, removal efficiencies were greater than 96%. Even though removal efficiency strongly depends on initial solute concentration, it is interesting to know that green roof substrate possesses good sorption efficiency towards a variety of metal ions. However,

![Fig. 2](image-url)
it is difficult to elucidate the exact removal mechanism of green roof substrate as several inorganic and organic constituents were mixed at different proportions. Several authors identified that vermiculite, perlite and coco-peat were able to bind several heavy metal ions. For instance, Sari et al. (2007) reported that expanded perlite exhibited 8.6 and 13.4 mg/g sorption capacities over Cu(II) and Pb(II) ions, respectively. On the other hand, exfoliated vermiculite sorbed 5.9, 8.4 and 8.6 mg/g of Ni, Cd and Cu, respectively; according to the Langmuir model (Álvarez-Ayuso and García-Sánchez, 2003). Parab et al. (2006) evaluated coconut pith for different metal ions and observed maximum adsorption capacities in the order of 13.8, 11.6, and 16.0 mg/g for Co(II), Cr(III) and Ni(II), respectively. Apart from these sorbents, Sargassum is known biosorbent for Pb, Cd, Cr, Cu, Zn and Ni (Romera et al., 2006; Vijayaraghavan et al., 2009). Considering the organic/inorganic constituents of green roof substrate, an overall negatively surface charge can be postulated in near neutral pH range. Under these conditions, the positively charged ions (e.g., Pb²⁺, Cd²⁺, etc.) were attracted towards negatively charged surface of the substrate. The column was terminated at 10 h since one of the heavy metal ions (Ni²⁺) exceeded the breakthrough limit. Analyzing the breakthrough profile of each heavy metal ion (Fig. 2), a consistent trend of gradual increase in exit metal concentration was observed. However, the extent of metal retained by green roof substrate varied with each metal ion. For instance, at 600 min, the C/C₀ (outlet concentration/inlet concentration) for Pb was less than 0.03 mg/L, as opposed to 0.101 mg/L for Ni. Based on the C/C₀ values at 600 min, the following order can be derived for green roof substrate: Pb < Cd < Cu < Cr < Al < Fe < Zn < Ni. This observation cannot be interpreted further as the initial solute concentration of each heavy metal ion was different. The affinity of a sorbent towards a particular metal ion in a multi-component

| Table 2 |
| Performance of green roof substrate loaded packed column during treatment of metal-spiked utility water. |

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Fe</th>
<th>Cr</th>
<th>Cu</th>
<th>Ni</th>
<th>Zn</th>
<th>Cd</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C/C₀) at 600 min</td>
<td>0.036</td>
<td>0.044</td>
<td>0.021</td>
<td>0.021</td>
<td>0.102</td>
<td>0.015</td>
<td>0.006</td>
<td>ND</td>
</tr>
<tr>
<td>Uptake (mg/g)</td>
<td>0.378</td>
<td>0.373</td>
<td>0.079</td>
<td>0.077</td>
<td>0.071</td>
<td>0.079</td>
<td>0.039</td>
<td>0.037</td>
</tr>
<tr>
<td>Removal efficiency (%)</td>
<td>97.4</td>
<td>96.4</td>
<td>98.5</td>
<td>98.6</td>
<td>92.5</td>
<td>99.6</td>
<td>99.6</td>
<td>99.6</td>
</tr>
</tbody>
</table>

ND: Not detected

Fig. 3. Runoff parameters from different green roof assemblies during un-spiked rain events (○) unspiked utility water; (□) runoff from GA-1; (○) runoff from GA-2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
solution depends on several factors including nature of binding sites, speciation of metal ions, concentration of metal ion, and competition from other metals (Vijayaraghavan and Yun, 2008). Further efforts were also made to determine uptake capacity and percentage removal efficiency of green roof substrate (Table 2). Even though green roof substrate exhibited a mediocre metal sorption capacity per gram of sorbent, it is important to note that these values represent only the column operation until 10 h. Also, it should be noted that the pollutant load at the rooftop level will be very low and sorption capacity exhibited by green roof substrate will be theoretically sufficient for the entire life-time of green roofs.

As illustrated in Fig. 2, green roof substrate showed no potential to sorb light metal ions. To be precise, significant leaching of Na, K, Ca and Mg were observed. These results were expected as these light metal ions are common elements in soil. Of these, potassium is an essential plant macro-nutrient, whereas Ca and Mg are essential micro-nutrients. The likely constituent responsible for light metal leaching from green roof substrate could be coco-peat, Sargassum, and vermiculite (Abad et al., 2002; Malandrino et al., 2006; Vijayaraghavan and Joshi, 2013). The magnitude of light metal leaching varied with column operation time. In general, high concentrations of these metals were observed in the effluent at the beginning of the event, followed by a gradual decrease as the time progressed (Fig. 2). Considering other parameters, green roof substrate-loaded column showed potential to slightly increase the runoff pH. Whilst conductivity and TDS were high at the start of the

Fig. 4. Runoff parameters from different green roof assemblies during metal-spiked rain events (○ metal-spiked utility water; □ runoff from GA-1; ▽ runoff from GA-2). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
experiment, they eventually depreciated as the time progressed (data not presented).

3.3. Runoff quality from green roofs

In our next effort, the influence of vegetated and non-vegetated green roofs on runoff quality was studied. For this purpose, two pilot-scale assemblies (GA-1 and GA-2) with different configurations were used. Foremost, rainfall simulation experiments (5–70 mm) were conducted using unspiked utility water. Interestingly, both green roof assemblies delayed runoff. This delay in runoff generation can be attributed to the combined effect of vegetation, substrate, drainage layer, local weather conditions and prior rain events. Of the two assemblies, GA-1 produced runoff after 20 mm, whereas the first appearance of runoff from GA-2 occurred only after 25 mm. The difference between the appearance of runoff in vegetated and non-vegetated assemblies was likely due to evapotranspirative and retention potential of plants, whose roots in the substrate layer retained water and slowed the release of water from the substrate layer (Berghage et al., 2007). Observing the same phenomenon, Speak et al. (2013) indicated that average runoff retention of 65.7% can be achieved on an intensive green roof (University of Manchester campus), compared to 33.6% on an adjacent paved roof.

Focusing on physico-chemical parameters, increased conductivity and TDS (total dissolved solids) of the outflow runoffs were observed from GA-1 and GA-2 (Fig. 3). This occurrence was mainly due to impurities/contaminants being leached from the substrate. Even though it is difficult to make quantitative source apportionment of pollutants, it is assumed that runoff pollutants would originate from substrate, roof material, vegetation, and atmospheric deposition (Berndtsson et al., 2009). Similar to column experiments, the high values of conductivity and TDS observed in the runoff during early stages ceased as the volume of rainfall increased (Fig. 3). For instance, 1117 µS/cm observed in the runoff originating from GA-1 at 20 mm declined to 933 µS/cm at 65 mm. Interestingly, GA-2 was found to be the least source of dissolved ions, based on conductivity and TDS values, suggesting that vegetation tends to utilize nutrients for growth and phyto-remediate other non-essential ions. Also it should be noted that the green roof assemblies were relatively new during the evaluation period and this suggests that more salts may be leached from new substrate than from the same roof once established. Results also confirm that GA-1 and GA-2 showed potential to decrease the pH of the influent to less than 8.

Runoffs from GA-1 and GA-2 were found to contain significant quantities of Na, K, Ca, Mg, Al, Fe, Cu, Ni, and Zn (Fig. 3). Whilst light metals were in higher concentrations, the concentration of heavy metals was less than 0.1 mg/L. The presence of P. grandiflora decreased the metal concentrations in the runoff, as evident from the results obtained from GA-2 (Fig. 3). Considering the fact that most of the examined metals are either macro- or micro-nutrients, essential for plant growth (Thenabadu, 1968), one can expect a decreased concentration of these metals in runoff from a vegetated-assembly compared to runoff from a non-vegetated assembly. Noticeable differences were observed in the cases of K and Ca concentrations during initial stages, wherein runoff from GA-1 recorded 59.8 mg K+/L and 98.8 mg Ca2+/L as opposed to only 19.8 mg K+/L and 71.5 mg Ca2+/L in the runoff from GA-2. Few research investigations pointed out that green roof acted as a source of pollutants; however, the concentrations of most of the metals were insignificant or well below permissible limits (Berndtsson et al., 2009; Vijayaraghavan et al., 2012). The reason for this could be due to be fact that most of the studies were conducted in mature green roof systems, in which continuous rainfall, plant uptake and other biological activities were expected to flush the pollutants out of the system. Conversely, the current study was conducted in a three-month old green roof system; hence it is not surprising that pollutant concentration in the runoff would be higher. These results clearly indicate that water quality of the runoff in the first year of a newly developed green roof may not be representative of the runoff of a mature and established roof.

Finally, the potential of GA-1 and GA-2 to retain metals was examined using spiked utility water in rainfall simulations. Similar to the results of non-spiked events, both assemblies delayed runoff in particular GA-2 retained rainfall till 20 mm. While focusing on runoff pH values, green roofs showed potential to increase the pH to near neutral/alkaline values. Average pH of inlet spiked-utility water was found to be in the range of 5.1–5.2 during all events. This pH range is intentionally used to simulate acidic rain, as the occurrence has created greater concern in recent years. As shown in Fig. 4, it is possible to neutralize the acidic pH with the aid of a green roof assembly. Buffering pH is one of the most significant and consistent effects of green roofs on water quality (Vijayaraghavan et al., 2012); and is highly useful in areas that are subject to acid rain. Considering conductivity and TDS of runoff, GA-1 recorded

<table>
<thead>
<tr>
<th>Contaminant/parameters</th>
<th>EPA recommended freshwater standards</th>
<th>Detection limit*</th>
<th>Level found in runoffs from GA-2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>During unspiked rain events</td>
</tr>
<tr>
<td>pH</td>
<td>6.5–9</td>
<td>–</td>
<td>7.6–7.8</td>
</tr>
<tr>
<td>Conductivity (µS/cm)</td>
<td>NIL</td>
<td>–</td>
<td>724–887</td>
</tr>
<tr>
<td>TDS (mg/L)</td>
<td>250</td>
<td>–</td>
<td>409–480</td>
</tr>
<tr>
<td>Na (mg/L)</td>
<td>NIL</td>
<td>0.069</td>
<td>541–112</td>
</tr>
<tr>
<td>K (mg/L)</td>
<td>NIL</td>
<td>0.2</td>
<td>101–19.8</td>
</tr>
<tr>
<td>Ca (mg/L)</td>
<td>NIL</td>
<td>0.01</td>
<td>29.8–71.5</td>
</tr>
<tr>
<td>Mg (mg/L)</td>
<td>NIL</td>
<td>0.016</td>
<td>28.1–41.2</td>
</tr>
<tr>
<td>Al (mg/L)</td>
<td>0.087</td>
<td>0.028</td>
<td>ND–0.04</td>
</tr>
<tr>
<td>Fe (mg/L)</td>
<td>1.0</td>
<td>0.004</td>
<td>0.02–0.03</td>
</tr>
<tr>
<td>Cr (mg/L)</td>
<td>0.57</td>
<td>0.007</td>
<td>ND</td>
</tr>
<tr>
<td>Cu (mg/L)</td>
<td>0.013</td>
<td>0.001</td>
<td>0.005–0.01</td>
</tr>
<tr>
<td>Ni (mg/L)</td>
<td>0.47</td>
<td>0.0025</td>
<td>0.004–0.019</td>
</tr>
<tr>
<td>Zn (mg/L)</td>
<td>0.12</td>
<td>0.005</td>
<td>0.008–0.041</td>
</tr>
<tr>
<td>Cd (mg/L)</td>
<td>0.002</td>
<td>0.0007</td>
<td>ND</td>
</tr>
<tr>
<td>Pb (mg/L)</td>
<td>0.042</td>
<td>0.0032</td>
<td>ND</td>
</tr>
</tbody>
</table>

ND: Not detected.

* Instrument manuals.
high values followed by GA-2. As expected, the values decreased as the events progressed.

The results clearly demonstrate that both assemblies acted as sink for all the heavy metal ions examined. Coinciding with column experimental results, both assemblies exhibited complete removal of heavy metal ions during initial rain events. Nevertheless, their concentrations increased gradually in the outlet runoffs as the events progressed (Fig. 4). For instance, Fe concentration of 0.009 mg/L at 20-mm rain event observed from GA-2, increased to reach 0.714 mg/L at the end of 65-mm. In the case of light metal ions, leaching was observed from examined green roofs. Comparing GA-1 and GA-2, the presence of P. grandiflora decreased the leaching of light metals and improved the sorption of heavy metals, as observed from the results of GA-2 (Fig. 4). As highlighted earlier, the sorption potential of various constituents present in green roof substrate play a major role in retention of heavy metal ions. In addition, plants can contribute to treatment efficiency in green roofs. The combination of CO₂ from root transpiration with hydrogen from soil water causes the formation of carbonic acid, which releases hydrogen ions (H⁺) from the substrate components. When these H⁺ ions exchange binding sites with other cations, those inorganic ions become available for root absorption (Berghage et al., 2007). Plants require mineral nutrients for their growth. After plant uptake, substrate binding sites become vacant, which in turn enables the substrate to adsorb additional elements from the influent contaminated water. For instance, Cd and Pb were completely absent in the runoff from GA-2 during entire 65-mm rain events. Conversely, GA-1 released Cd and Pb ions into the runoff within 30-mm.

Noting that GA-2 performed exceedingly well in retention of metal ions and generated better quality runoff, the results were compared with standards as proposed by the US Environmental Protection Agency for freshwaters (USEPA, 1986, 2009) (Table 3). Fresh-water standards were used because there are no standards to regulate the runoff quality from green roofs (Vijayaraghavan et al., 2012). As illustrated in Table 3, except TDS and Al, none of the other parameters/contaminant concentration exceeded EPA standards during spiked and unspiked events. Considering that the concentrations of metal ion were unrealistically high during spiked events, it is very encouraging to realize the high retention potential of green roofs. Even though an abundance of light metal ions was observed in the runoff, they subsided rapidly and reached levels that were the same as that of influent waters. Although there is no health advisory level for these elements, water with high dissolved solid content is considered as hard water. The total amount of metal ions retained by GA-2 during spiked rain events corresponds to 86.3, 85.4, 18.1, 17.5, 17.2, 17.9, 8.9 and 8.5 mg of Al, Fe, Cr, Cu, Ni, Zn, Cd and Pb, respectively. These values were very high in view of expected contaminant load at rooftop levels. For instance, we assumed 0.01 mg/L for metals such as Cu, Ni and Zn in rain water under normal circumstances in thickly populated urban areas. Under these circumstances, the examined green roof can filter approximately 7000 mm of rainfall without exceeding freshwater regulations. The presence of plants will further enhance the retention potential of green roofs due to continuous uptake of nutrients for growth and other non-essential elements as a result of phytoremediation.

4. Conclusions

This study investigated the possibility of green roofs to act as a sink for various metal ions. Based on the results, the following conclusions can be made:

Several low-cost inorganic aggregates (perlite, vermicultile, sand and crushed brick) and organic constituents (coco-peat and Sargassum biomass) were used to prepare green roof substrate. The developed green roof substrate had desirable characteristics of being light weight (bulk density = 487 kg/m³), providing free-draining of water (hydraulic conductivity = 4195 mm/h), storing water (WHC = 58.5%), and have adequate air space (AFP = 19.5%). Continuous-flow through experiments in a down-flow packed column using metal-spiked water exposed the excellent sorption capacity of green roof substrate towards different metal ions (Al, Fe, Cr, Cu, Ni, Zn, Cd and Pb). At the end of breakthrough time (10 h), the substrate exhibited high removal efficiencies of greater than 92.5% towards all metal ions.

Roof-top experiments using pilot-scale green roof assemblies planted with P. grandiflora were conducted to assess the runoff quality during different rain events. Runoff from green roof assemblies was found to comprise of high TDS and conductivity values along with some light metal ions. In particular, non-vegetated assemblies produced poor quality runoffs compared to vegetated assemblies. As the volume of rain increased, the quality of runoff improved.

During metal-spiked simulated rain events, green roof assemblies acted as pollutant sink for all heavy metal ions. At the end of 65 mm rain event, P. grandiflora planted green roof assembly retained 86.3, 85.4, 18.1, 17.5, 17.2, 17.9, 8.9 and 8.5 mg of Al, Fe, Cu, Ni, Zn, Cd and Pb, respectively. The above green roof assembly also showed potential to decrease the acidity of incoming water and delay runoff generation.

Thus, the developed substrate showed all desirable characteristics for successful implementation in extensive green roofs. Further research is needed especially to evaluate the suitability of substrate for other plant species as well as detailed stormwater attenuation potential.

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References


