Research Paper

Application of seaweed as substrate additive in green roofs: Enhancement of water retention and sorption capacity

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HIGHLIGHTS

• New green roof substrate was developed with Turbinaria conoides as additive.
• Substrate provided high moisture retention, air space and draining properties.
• Green roofs showed potential to delay runoff.
• Green roofs acted as sink for various heavy metal ions with high sorption capacity.

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ABSTRACT

Green roof substrates are usually designed to achieve desirable characteristics such as low bulk density, preparation cost, high water holding capacity (WHC), hydraulic conductivity (HC) and airfilled porosity (AFP). However, no importance is given to sorption capacity or leaching potential of substrate. Thus, in the present study, novel attempt was made to incorporate a brown-seaweed (Turbinaria conoides) in growth substrate to enhance the runoff quality from green roofs. The green roof substrate, prepared using 30% perlite, 20% vermiculite, 10% sand, 20% crushed brick, 10% cocopeat and 10% T. conoides, was found to have favourable characteristics such as low bulk density (477.7 kg/m3), high WHC (49.5%), AFP (20.5%) and HC (4210 mm/h). With the aid of down-flow fixed column, sorption capacity of green roof substrate towards various metal ions (Na, K, Ca, Mg, Al, Fe, Cd, Cu, Cr, Ni, Pb and Zn) was examined and results indicated that the column was able to operate for 1440 min at a flow rate of 5 ml/min before outlet Ni concentration reached the inlet. Green roof experiments were performed using pilot-scale assemblies with Portulaca grandiflora as vegetation. Under rainfall simulations, it was observed that vegetated-green roof assemblies acted as a sink for various metal ions and produced better runoff. In addition, green roofs buffered acidic rain and delayed runoff generation.

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1. Introduction

With the rapid urbanization, tall buildings and other new developments are made at the expense of green areas in cities. This resulted in shortage of greenery which in turn causes a decrease in canopy interception and transpiration within the city leading to increased temperature and decreased air humidity (Berndtsson, 2010). In addition, buildings are also responsible for 33% of greenhouse gas emission globally through high rate of energy and resource consumption (Berardi, Ghaffarianhoseini, & Ghaffarianhoseini, 2014). These problems may be partially solved by altering buildings’ rooftop properties. In recent years, green roofs (also called as vegetated roofs, living roofs or eco-roofs) are identified as a practical and valuable strategy to make sustainable buildings in urban areas.

Green roofs are basically roofs planted with vegetation on the top of growth medium (substrate). Depending on the location and space availability, green roofs generally comprise of vegetation at the top, followed by substrate, filter fabric, drainage element, root barrier, insulation and waterproofing layer. Green roofs present numerous economic and social benefits in addition to more obvious environmental advantages such as: improved insulation of the building; stormwater attenuation; noise insulation; reduced heat-island effect; extended roof life; habitat for pollinators; aesthetic value and enhanced marketability of property; improved air quality.
(Bates, Sadler, Greswell, & MacKay, 2015; Berardi et al., 2014; Chen, 2013). As a result of these positive effects, green roofs are becoming popular in many countries (Chen, 2013; Vijayaraghavan & Raja, 2014a). Several large-scale green roofs were established in European, American and few Asian countries. However, recent research reports pointed out that most of the commercial green roofs are not optimized to achieve the environmental/economic benefits associated with greening the rooftops (Berndtsson, 2010). To be precise, the focus of commercial green roof developers is usually related with development of substrate mix and management (watering and fertilization) to support vegetation. The performance of green roofs towards achieving various benefits is not well known. One such important benefit of green roof is enhancement of storm-water runoff quality. However, recent research reports proved that green roofs can also potentially degrade the quality of rain water with pollutants released from soil, plants and fertilizers (Berndtsson, Emilsson, & Bengtsson, 2006; Moran, Hunt, & Jennings, 2003; Vijayaraghavan & Joshi, 2014). Rainwater is generally considered as non-polluted but may be acidic, and contains substantial amounts of nitrates and traces of other pollutants such as heavy metals and pesticides depending on the local pollution sources and prevailing winds (Berndtsson, 2010). Upon percolation through green roof system, ions from substrate components will be leached into the influent and the runoff will have a higher concentration of the ion than the rain water (Gnecco, Pallà, Lanza, & La Barbera, 2013). This is further complicated by plant uptake and fertilization practices which remove or add nutrients, respectively. However, till now, only runoff quality assessment studies were performed (Teemusk & Mander, 2007; Vijayaraghavan & Joshi, 2014) and no in-depth investigation has been made to improve the quality of runoffs generated by green roofs. The improvement in the runoff quality from green roofs can be achieved through proper selection of substrate components and plants. Green roof substrates should be light weight, cheap, and possess high water retention capacity, hydraulic conductivity and air-filled porosity. However, no importance was given to sorption capacity or leaching potential of substrate. Considering the green roof substrate mainly comprise of inorganic constituents, it is advisable to mix an efficient sorbent which improve the sorption capacity of green roof substrate. Therefore, through this study, a brown-seaweed (Turbinaria conoides) was supplemented with the green roof substrate to enhance the sorption capacity as well as support plant growth. T. conoides is a well-known sorbent for various heavy metal ions (Vijayaraghavan, Joshi, & Kamala-Kannan, 2012) and it comprise of high NPK ratio (Sunarpi, Jupri, Kurnianingsih, Julisaniah, & Nikmatullah, 2010). Therefore, the objective of the present study was to develop a novel seaweed-based growth substrate for green roofs. Packed column assembly was used to evaluate sorption capacity of substrate, whereas pilot-scale green roof assemblies were employed to examine the runoff quality and plant support.

2. Materials and methods

2.1. Substrate components and mixture preparation

Based on the procedures developed by Vijayaraghavan and Raja (2014a), green roof substrate was developed using expanded perlite, exfoliated vermiculite, sand, crushed brick and coco-peat. The substrate exhibited favourable physico-chemical properties as well as supported maximum plant growth. However, the sorption capacity was found to be limited. Thus, in the present study, the organic content (coco-peat) was replaced with equal volume mix of T. conoides and coco-peat. The modified green roof growth substrate comprises of (on volume basis) 30% perlite, 20% vermiculite, 10% sand, 20% crushed brick, 10% coco-peat and 10% T. conoides. Expanded perlite (0.25–1 mm) was purchased from Keltech Energies Ltd. (Bangalore, India), whereas exfoliated vermiculite (0.5–2 mm) was procured from Siriramamuruti Vermiculite Mines (Chennai, India). Other inorganic constituents (sand (0.25–1 mm) and crushed brick (4–10 mm)) were obtained from commercial shops. Samples of T. conoides were collected from the Mandapam region of Tamil Nadu, India. Coco-peat samples were collected from a local nursery. Both organic constituents were initially dried under sunlight for three days and 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 were 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 FLILied guidelines (FLIL, 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).

2.2. Preparation of metal-spiked water

Metal-spiked water was prepared by artificial addition of metal ions by mixing their respective nitrate salts in either deionized (DI) or rain water. Analytical grades of NaNO3, KNO3, Ca(NO3)2·4H2O, Mg(NO3)2·6H2O, Al(NO3)3·9H2O, Fe(NO3)3·9H2O, Cr(NO3)3·9H2O, Zn(NO3)2·6H2O, Cu(NO3)2·3H2O, Ni(NO3)2·6H2O, Pb(NO3)2 and Cd(NO3)2·4H2O were purchased from Sigma–Aldrich, India. To decide upon the concentration to be spiked, metal ions were classified into four groups: non-toxic (Na, K, Ca and Mg), mild-toxic (Al and Fe), toxic (Ni, Zn, Cu and Cr) and highly toxic (Pb and Cd) metals. In the spiked–rain or DI 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-metal toxic ions, respectively (Vijayaraghavan & Raja, 2014a).

2.3. Sorption experiments

Continuous-flow experiments were conducted in a downflow packed column (height = 35 cm; internal diameter = 2.5 cm). Around 55.9 g of green roof substrate was loaded within the column to obtain a bed height of 25 cm. In order to distribute the influent uniformly, a 3 cm layer of glass beads was placed at the top of the column. The influent (metal-spiked DI water) at pH 5.5 was pumped downwards through the column at a flow rate of 0.3 L/h using a peristaltic pump. Samples were collected at the column exit at regular time intervals and analyzed immediately for metal concentrations using inductively coupled plasma-optical emission spectrometry (ICP-OES, Perkin Elmer Optima 5300 DV). Column uptake and % removal were calculated according to Vijayaraghavan and Yun (2008). The total quantity of metal mass adsorbed in the column is calculated from the area above the breakthrough curve (outlet metal concentration vs. time) multiplied by the flow rate. Dividing the metal mass by the substrate mass (M) leads to the uptake capacity (Q) of the substrate. On the other hand, metal removal efficiency (%) with respect to flow volume can be calculated from the ratio of metal mass adsorbed to the total amount of metal ions sent to the column.

2.4. Study site and green roof components

Green roof experiments were carried out on the rooftop of Mechanical Sciences Block (IIT Madras, India). Pilot-scale green roof assemblies (50 cm × 50 cm × 25 cm glass) were designed and were
placed on a table at a 4° slope to simulate common roof design. The runoff was collected in a measuring beaker through the opening at the bottom of the assembly. Each assembly composed of three components (Fig. 1) with the uppermost being a substrate layer comprising of a 10 cm thick green roof substrate. The intermediate was a filter layer in the form of a geotextile, which prevent small particles from being washed from the substrate layer into the drainage layer or out of the system. The third was a drainage layer in the form of a commercial drainage element (flexible drain cell, Bioremegree Technology Solutions, India). The commercial drainage element 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.

*Portulaca grandiflora* was used as green roof vegetation in the present study. The plant species possess inherent advantages such as ability to withstand drought conditions, good ground coverage, less maintenance, rapid multiplication, and have short and soft roots for successful implementation in green roofs (Vijayaraghavan & Raja, 2014a). One-month-old cuttings of *P. grandiflora* grown in commercial garden soil were purchased from a local nursery. As the cuttings had been grown in commercial mix, they were washed in water before planting to reduce the effects of the commercial media on the green roof substrate. The vegetation was then planted in the green roof assembly at a density of 64 plugs/m². During the course of adaptation, artificial watering (200 mL) was provided every 2 days. A small tent-like structure was constructed during experiment to protect the boxes from rainfall interference. After 1 month of plant establishment in boxes, field experiments were conducted.

### 2.5. Rainfall simulation experiments

In an attempt to understand the influence of green roofs on runoff quality, rainfall events were simulated on two pilot-scale green roof assemblies. Two identical green roof pilot-scale assemblies were employed in the present experiments. The design of each assembly is based on commercial green roofs (Department of Design and Construction, 2007). The first assembly (GRA-1) comprise of drainage element, geo-textile membrane and green roof mix substrate; whereas the second (GRA-2) comprise of drainage element, geo-textile membrane and green roof mix substrate planted with *P. grandiflora* (Fig. 1). The two assemblies were compared to understand the role of vegetation on runoff quantity and quality. Rain events (5–65 mm) were simulated manually with a sprinkler equally on each assembly at an intensity of 10 mm/h. Runoff samples were collected at the exit of each assembly for each rain event for the analysis of various physico-chemical parameters. Once there was no sign of runoff, the assembly was left undisturbed for 1 h before further experimentation. In total, 10 runoff events were considered with one event amounting to 5 mm. To elucidate metal retention capacity of green roofs, simulated rain events were conducted using metal-spiked rain water. Runoff samples collected during 10 runoff events were analyzed as that of un-spiked events.

### 3. Results and discussion

#### 3.1. Characteristics of green roof substrate mix

Substrates used on green roofs are mainly composed of inorganic material and minimal organic constituents (Department of Design and Construction, 2007; FLL, 2002). This is to achieve low dense, minimal nutrient and highly stable green roof substrates. In the present study, green roof substrate was prepared to be composed of 80% inorganic (perlite, vermiculite, sand and crushed brick) and 20% organic (coco-peat and *T. conoides*). The particle size of substrate mix was in the range of 0.25–10 mm. This was intentional to alter the volume of air and water held by the final green roof substrate mix. The bulk density was determined as 477.7 kg/m³ and this value was significantly lower than those reported in the literature (Cao, Farrell, Kristiansen, & Rayner, 2014; Farrell, Mitchell, Szota, Rayner, & Williams, 2012). Low bulk density of prepared green roof substrate is due to coco-peat, *T. conoides*, perlite and vermiculite, whose bulk densities were in the order of 115, 406.4, 148 and 279 kg/m³, respectively. Hydraulic conductivity was determined as 4210 mm/h and this value was significantly higher than FLL guidelines for green roofs, which states that efficient green roof substrate should have hydraulic conductivity greater than 3600 mm/h (FLL 2002). High values of hydraulic conductivity are preferable to avoid water ponding on the surface of the substrate, which in turn add weight that may overload the structure or run laterally and erode the substrate from the roof. Furthermore, WHC and AFP of green roof substrate were calculated as 49.5 and 20.5%, respectively. These values were well above the minimum requirements for a green roof substrate (WHC > 20% and AFP > 10%), according to FLL guidelines. The presence of *T. conoides* (WHC = 170%), vermiculite (WHC = 62.5%) and coco-peat (WHC = 46.3%) improved the overall WHC of substrate mix. On the other hand, the presence of crushed brick (AFP = 28.3%) and perlite (AFP = 31.1%) enhanced AFP of final mix. Both WHC and AFP are crucial for superior plant growth. Thus through preliminary analysis,
the prepared substrate mix showed desirable characteristics to be employed in green roofs.

3.2. Packed column experiments

Initial experiments were performed to evaluate the sorption potential of prepared substrate mix in continuous mode of operation. Fig. 2 represents breakthrough curves of examined metal ions. Important column parameters including the column metal uptake capacity, % metal removal and \( C/C_0 \) (outlet metal concentration/inlet metal concentration) during entire column operation are presented in Table 1. Since different metal ions of varied regulatory limits have been present in the spiked DI water, column breakthrough was obtained when any of the outlet heavy metal ion concentration reached influent value.

It is evident from the results presented in Table 1 and Fig. 2 that substrate mix performed very well in continuous removal of heavy metal ions from metal-spiked DI water. The column was operated for 24 h and substrate mix showed good uptake capacity towards all metal ions. This accounts to 59 bed volumes or 7.2 L of spiked DI water treated. It is interesting to note that Zn, Pb and Cd ions were detected in the outlet only after 240, 420 and 360 min, respectively. This corresponds to total removal efficiency greater than 96.6% for these heavy metal ions (Table 1). On the other hand, substrate mix was able to retain Cu and Cr to undetectable limits until 75 and 40 min of column operation, respectively. Although removal efficiency strongly depends on initial metal concentration, it is encouraging to know that substrate mix possesses good sorption efficiency towards variety of metal ions. It is interesting to note that the performance of substrate mix towards Al and Fe ions during initial stages of column operation was relatively uneven (Fig. 2). As these ions (Al and Fe) were natively present in some of the constituents used to prepare the substrate mix, some leaching into the solute was always expected. However, the substrate mix showed good sorption capacity towards Al and Fe in the later stages of column operation. The column operation was eventually stopped at 1440 min since nickel concentration in the outlet reached that of influent. The earlier breakthrough of nickel compared to other metal ions may be due to less affinity of Ni\(^{2+}\) towards substrate mix. The affinity of a sorbent towards a particular solute in a multi-metal solution depends on several factors including nature of binding sites, speciation of metal ion, concentration of metal ion, and competition from other metals (Vijayaraghavan & Yun, 2008). Since the sorbent (green roof substrate) is a mixture of several components and the metal ions spiked in the DI water were of varied concentrations, it is difficult to elucidate the mechanism of metal removal and thus considered as beyond the scope of the present study. Nevertheless, the presence of T. conoides along with other constituents such as coco-peat and vermiculite were responsible for the high sorption capacity of substrate mix (Mathialagan & Vriragahavan, 2003; Parab et al., 2006; Vijayaraghavan et al., 2012). The overall sorption uptake capacities along with % removal were determined and are presented in Table 1. Very high % removal efficiencies greater than 91.7% was observed for all heavy metal ions except Ni.

Monitoring the concentration profiles of major cations (Na, K, Ca and Mg) presented some interesting results (Fig. 2), with the substrate mix able to retain Ca and Mg during entire column operation. However, the substrate mix only acted as a source for Na and K ions. The substrate also showed potential to increase the outlet pH as evident from Fig. 2.

3.3. Pilot-scale green roof experiments

3.3.1. Unspiked rain events

The runoff quality from green roofs was examined using pilot-scale green roof assemblies (GRA-1 and GRA-2). Initially, the runoff characteristics of green roofs were evaluated using unspiked rain water. Figs. 3 and 4 represents important water quantity and quality characteristics, respectively, of runoffs originated from green roof assemblies during different rain events.

Both GRA-1 and GRA-2 delayed runoff as evident from Fig. 3. Due to the combined effect of vegetation, substrate, drainage layer, local weather conditions and prior rain events, green roof delay peak flow (Berndtsson, 2010). For the present system, drainage layer, substrate and vegetation played a major role in peak flow reduction. As discussed in Section 3.1, green roof substrate exhibited high WHC of 49.5%. In addition, the drainage module used in the present study can store water up to 2 L/m². The influence of vegetation in peak flow reduction can be clearly seen from the results of GRA-1.
and GRA-2; wherein due to the presence of *P. grandiflora*, GRA-2 produced runoff only after 20 mm of rainfall. This 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).

Both assemblies showed potential to produce alkaline runoffs (Fig. 4). Concurrently, the runoffs were also identified to be comprised of high dissolved solids as evident from conductivity and TDS values (Fig. 4). These high values were 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, Bengtsson, & Jinno, 2009). The runoff pH values were significantly higher during initial events; however, decreased sharply and approached inlet pH values as rain events progressed. Similar trend was observed with conductivity and TDS values, where high values observed during initial stages and depreciated as...

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**Fig. 3.** Runoffs generated from different green assemblies during unspiked and metal-spiked rain events.

**Fig. 4.** Runoff water quality parameters from different green roof assemblies during unspiked rain events (♦ unspiked rain water; □ runoff from GRA-1; ○ runoff from GRA-2).
Fig. 5. Runoff water quality parameters from different green roof assemblies during metal-spiked rain events (diamond) metal-spiked rainwater; (square) runoff from GRA-1; (circle) runoff from GRA-2.

Table 2
Performance of green roof assemblies during metal-spiked rain events.

<table>
<thead>
<tr>
<th>Assemblies</th>
<th>Al</th>
<th>Fe</th>
<th>Cu</th>
<th>Cr</th>
<th>Ni</th>
<th>Zn</th>
<th>Pb</th>
<th>Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRA-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>(C/C0) at 60 mm</td>
<td>0.091</td>
<td>0.18</td>
<td>0.021</td>
<td>0.025</td>
<td>0.053</td>
<td>0.014</td>
<td>0.010</td>
<td>0.014</td>
</tr>
<tr>
<td>(Metal retained) at 60 mm (mg)</td>
<td>73.5</td>
<td>71.9</td>
<td>15.3</td>
<td>15.0</td>
<td>15.0</td>
<td>14.8</td>
<td>7.40</td>
<td>7.49</td>
</tr>
<tr>
<td>GRA-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(C/C0) at 65 mm</td>
<td>0.059</td>
<td>0.12</td>
<td>0.005</td>
<td>0.014</td>
<td>0.028</td>
<td>0.006</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(Metal retained) at 65 mm (mg)</td>
<td>80.1</td>
<td>78.6</td>
<td>16.6</td>
<td>16.4</td>
<td>16.4</td>
<td>16.2</td>
<td>8.04</td>
<td>8.14</td>
</tr>
</tbody>
</table>
the volume of rain increases. For example, 315 μS/cm observed for runoff originated from GRA-2 after 20 mm decreased to 127 μS/cm at the end of 65 mm. Considering that the green roof assemblies were relatively new during the evaluation period, more contaminants may be released from the growth substrate. However their concentrations are expected to cease, as evident from the present results, with continuous rainfall. Interestingly, the presence of P. grandiflora further decreased the conductivity and TDS values of runoffs (Fig. 4). Taking into account that plants utilize nutrients for growth and phytoremediate other non-essential ions (Tak, Ahmad, & Babalola, 2013), it is not surprising to observe less ion content in the runoffs generated from vegetated assemblies.

Leachates from both assemblies were found to comprise of significant quantities of major cations (Na, K, Ca and Mg) as well as minor quantities of heavy metals (Al, Fe, Cu, Zn and Ni). Nevertheless, the magnitude of leaching varied with each green roof assembly. It should also be noted that runoffs from GRA-1 and GRA-2 were devoid of metals such as Cr, Cd and Pb. In the present study, the growth substrate plays a vital role in altering the runoff quality which was previously also noted in column experiments (Section 3.2). However, the presence of P. grandiflora in GRA-2 enabled the assembly to produce relatively less-contaminated runoff. Considering that most of the examined metals are either macro- or micro-nutrients, essential for plant growth (Thenabadu, 1968; Tak et al., 2013), decreased concentrations of metals were observed in vegetated assembly. For instance, average K concentration leached during entire 10 events from GRA-1 was found to be 47 mg/L as opposed to only 10.5 mg/L from GRA-2. Similarly, GRA-2 released only 19.5 mg Na/L, 19.7 mg Ca/L, 27.5 mg Mg/L, 0.03 mg Al/L, 0.02 mg Fe/L, 0.01 mg Cu/L, 0.02 mg Zn/L and 0.01 mg Ni/L on an average during entire 10 events. In contrast, GRA-1 leached 27.5 mg Na/L, 30.0 mg Ca/L, 39.3 mg Mg/L, 0.04 mg Al/L, 0.03 mg Fe/L, 0.02 mg Cu/L, 0.06 mg Zn/L and 0.02 mg Ni/L in the runoffs during 10 events. It should be noted that the leached metals are important elements in soil and are often present in large quantities in minerals. For instance, vermiculite comprises of 14.6% Al2O3, 16.1% Fe2O3 and 9.68% MgO (Vijayaraghavan & Raja, 2014c); whereas perlite constitutes 12–18% Al2O3, 4–5% K2O and 2.9–4% Na2O (Vijayaraghavan & Raja, 2014b).

### 3.3.2. Metal-spiked rain events

To evaluate the potential of green roofs to act as sink for various metal ions, further experiments were conducted with acidic metal-spiked rainwater as the influent. Similar to the results of non-spiked rain events, both assemblies delayed runoff in particular GRA-2 retained rainfall till 20 mm (Fig. 3). Green roofs have unique benefit of buffering acidic rainfall (Teemusk & Mander, 2007; Vijayaraghavan & Joshi, 2014). This was proved in our experiments, as influent pH (5.0) rapidly increased to 6.3 during first event and attained slightly alkaline values as the events progressed. The ability of a green roof to neutralize acid rainfalls is a major environmental benefit especially for highly industrialized countries. Results also revealed that runoffs from GRA-1 were more polluted as reflected from conductivity and TDS values (Fig. 5), compared to runoffs from GRA-2.

Percolation of metal-spiked rainwater through green roofs, with or without plants, effectively reduced concentrations of all heavy metal ions. This effect was more pronounced in GRA-2 than GRA-1 (Fig. 5). The synergic effect of growth substrate and P. grandiflora enabled GRA-2 to act as an excellent sink for heavy metal ions. As discussed earlier (Section 3.2), 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 enhance the treatment efficiency of 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.

Analysing the results (Fig. 5), it is interesting to note that the runoff from GRA-2 were completely devoid of Cd and Pb during entire 10 events. Higher atomic weight and ionic radius favoured these metals to be sorbed more than other metal ions (Vijayaraghavan & Yun, 2008). Conversely, GRA-1 released Cd and Pb ions into the runoff within 40 mm of rainfall (Fig. 5). The performance of GRA-2 towards other metal ions was also comparatively higher as Cu, Zn, Cr and Ni appeared only after 55, 65, 55 and 40 mm of rain events. Even though the concentration of above metal ions increased as the rain event progressed, the values were insignificant compared to influent concentrations. The total amount of metal ions retained by GRA-2 during metal-spiked rain events are presented in Table 2. Results indicated than GRA-2 retained more metal ions compared to GRA-1. Interestingly, the C/Co values were only 0.005, 0.006, 0.014 and 0.028 for Cu, Zn, Cr, and Ni, respectively, at the end of 65 mm in GRA-2. For other metal ions such as Al and Fe, GRA-2 showed good retention capacity during early stages; however, runoffs from GRA-2 found to be comprised of Al and Fe as the events progressed. It should be noted that initial concentrations of both these metal ions were relatively higher than other heavy metals examined. At the end of 65 mm, C/Co values of Al and Fe were 0.059 and 0.12, respectively. On comparison, C/Co values of metal ions from GRA-1 were higher than those observed in GRA-2 (Table 2).

### 4. Conclusions

It has been shown through the results of the study that green roofs could act as sink for several heavy metal ions due to the presence of *T. conoides* in the growth substrate. The specific conclusions are as follows:

- **Green roof growth substrate comprising (on volume basis) 30% perlite, 20% vermiculite, 10% sand, 20% crushed brick, 10% coir peat and 10% *Turbinaria* biomass can provide high moisture retention capacity, air space and draining properties.**
- **Column experiments using up-flow fixed bed highlighted the high sorption capacity of green roof substrate towards heavy metal ions such as Al, Fe, Cd, Cu, Cr, Ni, Pb and Zn.**
- **Green roof showed potential to delay runoff generation and buffer acidic rainfall. Pilot-scale experiments also revealed that vegetation (*P. grandiflora*) and growth substrate played a vital role in alteration of runoff quality.**
- **A substantial dissolved solid, in particular light metal content was observed in runoff emanated from green roofs which is likely due to leaching from growth substrate. However, the presence of vegetation in green roofs substantially depreciated TDS content.**
- **For all of the studied physico-chemical parameters, the values were spiked at the start of the event; however gradually declined as the volume of rainfall increases. This clarifies an important aspect that newly established green roofs produce more pollution than matured/established green roofs.**
- **Metal-spiked rain events indicated that *P. grandiflora* planted green roofs acted as sink for various metal ions, and metal retained until 65 mm accounts to 80.1, 78.6, 16.6, 16.4, 16.1, 8.04 and 8.14 mg of Al, Fe, Cu, Cr, Ni, Zn, Pb and Cd, respectively.**
- **Thus, through this study, we suggest that the selection of substrate for green roofs should not be completely based on bulk density, moist weight, hydraulic conductivity and plant support,**
but attention should also be provided to sorption capacity of substrate.

- Future studies should focus on long-term evaluation of runoff quality from green roofs and this could incorporate leaching/sorption of substrate and the phytoremediation potential of vegetation under real rainfall events.

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