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Design and development of green roof substrate to improve runoff water quality: Plant growth experiments and adsorption

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ABSTRACT

Many studies worldwide have investigated the potential benefits achievable by transforming brown roofs of buildings to green roofs. However, little literature examined the runoff quality/sorption ability of green roofs. As the green roof substrate is the main component to alter the quality of runoff, this investigation raises the possibility of using a mixture of low-cost inorganic materials to develop a green roof substrate. The tested materials include exfoliated vermiculite, expanded perlite, crushed brick and sand along with organic component (coco-peat). Detailed physical and chemical analyses revealed that each of these materials possesses different characteristics and hence a mix of these materials was desirable to develop an optimal green roof substrate. Using factorial design, 18 different substrate mixes were prepared and detailed examination indicated that mix-12 exhibited desirable characteristics of green roof substrate with low bulk density (431 kg/m^3), high water holding capacity (39.4%), air filled porosity (19.5%), and hydraulic conductivity (4570 mm/h). The substrate mix also provided maximum support to *Portulaca grandiflora* (380% total biomass increment) over one month of growth. To explore the leaching characteristics and sorption capacity of developed green roof substrate, a down-flow packed column arrangement was employed. High conductivity and total dissolved solids along with light metal ions (Na, K, Ca and Mg) were observed in the leachates during initial stages of column operation; however the concentration of ions ceased during the final stages of operation (600 min). Experiments with metal-spiked deionized water revealed that green roof substrate possess high sorption capacity towards various heavy metal ions (Al, Fe, Cr, Cu, Ni, Pb, Zn and Cd). Thus the developed growth substrate possesses desirable characteristics for green roofs along with high sorption capacity.

1. Introduction

Green roofs also referred as living-, vegetated-, and eco-roofs are roofs covered with substrate and plants. They can be classified into extensive and intensive green roofs, based on the depth of the substrate (Osmundson, 1999; Snodgrass and McIntyre, 2010). Extensive green roofs comprise a substrate layer with a maximum depth of about 150 mm and thus would typically support vegetation of type succulents, herbs, grasses,

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and mosses. In contrast, substrate depth of intensive green roof can be more than 150 mm, which can support woody plants (Rowe, 2011). Public and research interests in green roofs have increased in recent years, most probably as a result of the variety of unique environmental benefits that are frequently attributed to them. These benefits include their ability to reduce building energy consumption, reduce noise level, improve air quality, runoff volume control during storm events, minimize urban heat island effect, building aesthetics and help solar panels to perform better (Dunnett and Kingsbury, 2004; Berndtsson, 2010; Aitkenhead-Peterson et al., 2011; Bates et al., 2013). Many countries and municipalities understand these benefits and started to implement or even mandate green roofs in buildings. Green roof coverage in Germany alone now increases by approximately 13.5 million square meters per year (Oberndorfer et al., 2007). In Toronto, the green roof by-law requires all new development with a gross floor area of $\geq$2000 m^2 to include a green roof on 20–60% of the roof area (Chen, 2013). In general, green roof has now been recognized as a practicable solution to increase the greenery coverage and re-establish the vanishing green space in the urban areas.

Green roof technology is well-established in Europe, North America and few Asian countries. In-depth investigations have been published on the green roof systems installed in these countries (Moran et al., 2003; Berndtsson et al., 2006; Vijayaraghavan et al., 2012). However, green roofs are yet to catch up in Asian countries such as India. There has been no local research study focussed on green roofs; and hence no public and government awareness. Being energy deficit and flood prone country, green roofs have great potential in India. To enhance awareness, broader investigation on suitability of green roofs for the local conditions and cost analysis should be performed. Due to the difference in climatic condition and form of development of urban area, it is also well known that the commercial green roof systems from Western nations or other countries might not be completely adopted and adapted to the local context (Wong and Lau, 2013). Hence, efforts should also be made to screen suitable vegetation and substrate materials applicable for local conditions.

Green roofs generally comprise of several components, including vegetation, substrate, filter fabric, drainage material, root barrier and insulation. Very few studies analysed the role of these components on the unique benefits of green roofs (Nagase and Dunnett, 2011; Pérez et al., 2012; Vijayaraghavan et al., 2012); otherwise the impact of these components is very little understood. For instance, runoff water quality from green roofs is relatively unknown. Theoretically, green roofs can act as pollution adsorbents and filters. However, they can also potentially contribute to the degradation of the quality of receiving waters with pollutants released from soil, plants and fertilizers (Teemusk and Mander, 2007; Vijayaraghavan et al., 2012). Several authors observed presence of heavy metals and other contaminants in the runoff from green roof systems (Alsup et al., 2011; Speak et al., 2014). Berndtsson et al. (2006) found that while in lower concentrations than normally found in urban runoff, some metals appear in runoff from green roofs in concentrations that would correspond to moderately polluted natural water. The degradation of runoff quality could be related to usage of fertilizers, and improper selection substrate and plants (Rowe, 2011). Phytoremediation ability was never a criterion for selection green roof plants. Substrate components were not screened based on their adsorption/biosorption capacity or less leaching tendency. If green roofs are to be considered environmentally benign as well as to meet long-term client expectations, then selection of efficient green roof components are extremely important.

Thus the objective of present study was to develop a green roof substrate using different low-cost materials to improve runoff quality. Pot experiments were conducted using *Portulaca grandiflora* as test species. The substrate was optimized based on water retention capacity, air filled porosity, hydraulic conductivity, bulk density, sorption capacity, and plant support. Based on the above results, the optimized substrate mix will be recommended for further testing in pilot-scale green roofs to examine the impacts of wind, rain, foot-traffic and nutrient depletion.

2. Materials and methods

2.1. Substrate materials and plant

The materials used for the preparation of green roof substrate include exfoliated vermiculite, expanded perlite, crushed brick, sand and coco-peat (29% moisture content). These materials were obtained locally and used in their original form in experiments. The physical and chemical characteristics of these substrate components are listed in Table 1.

P. grandiflora was chosen as test plant species for the present study. The plant species in the form of cuttings were purchased from a commercial nursery. *P. grandiflora* possess several advantages which are essential for green roof plants such as ability to thrive in extreme dry and water scarcity conditions, have short and soft roots (DDC, 2007), and provide excellent ground cover.

2.2. Substrate preparation and analysis

For the present study, substrate preparation was based on extensive green roof system. Hence, depth of substrate was fixed at 10 cm with 80% inorganic and 20% organic composition (DDC, 2007). The inorganic constituents used include vermiculite, perlite, crushed brick, and sand; whereas 20% coco-peat was used in all experiments unless otherwise indicated. We have used factorial design to optimize the composition of green roof substrate. In total, 18 different substrate mixes (Table 2) with replicates were examined to achieve maximum plant biomass, water retention potential, air filled porosity and minimum bulk density.

Physico-chemical parameters of green roof substrate components were measured by contacting 1 g of substrate components with 100 mL of deionized (DI) water in an Erlenmeyer flask. The contents were then agitated in a rotary shaker for 24 h at 30 ± 2 °C. The supernatant was filtered through 0.45 μm PTFE membrane filter and the filtrate was analysed for pH, conductivity, total dissolved solids (TDS), light and heavy metal ions. In the case of analysis of metals (Na, K, Ca, Mg, Al, Fe, Cu, Cd, Pb, Zn, Cr, and Ni), inductively coupled plasma- optical emission spectrometry (ICP-OES,