Science of the Total Environment 592 (2017) 465–476

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

The influence of dual-substrate-layer extensive green roofs on rainwater runoff quantity and quality

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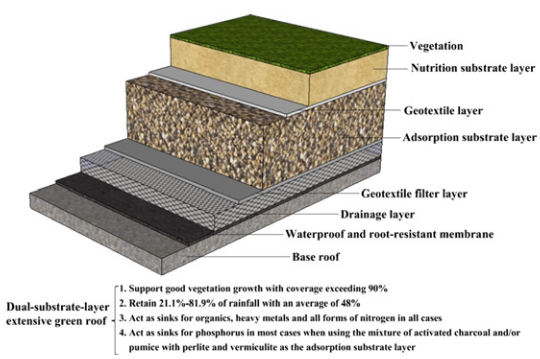
HIGHLIGHTS

- Dual-substrate-layer (DSL) extensive green roofs were effective at retaining rainfall.
- DSL green roofs were sinks for organics, heavy metals and nitrogen in all cases.
- DSL green roofs were able to mitigate mild acid rain.
- DSL green roofs' runoff did not show any first flush effect.
- DSL green roofs were practical in application for retaining rainwater in urban areas.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 23 December 2016
Received in revised form 12 March 2017
Accepted 12 March 2017
Available online 17 March 2017

Editor: Simon Pollard

Keywords:
Green roof
Dual-substrate-layer
Organic nutrition layer
Inorganic adsorption layer
Activated charcoal
Pumice

ABSTRACT

This study investigates the ability of dual-substrate-layer extensive green roofs to retain rainwater and reduce pollutant leaching. The substrates in dual-substrate-layer green roofs consist of an upper organic nutrition layer for plant growth and a lower inorganic adsorption layer for water retention and pollutant reduction. One traditional single-substrate-layer extensive green roof was built for comparison with dual-substrate-layer green roofs. During the experimental period, dual-substrate-layer green roofs supported better natural vegetation growth, with coverage exceeding 90%, while the coverage in single-substrate-layer green roof was over 80%. Based on the average retention value of the total rainfall for four types of simulated rains (the total rainfall depth (mm) was 43.2, 54.6, 76.2 and 86.4, respectively), the dual-substrate-layer green roofs, which used the mixture of activated charcoal with perlite and vermiculite as the adsorption substrate, possessed better rainfall retention performance (65.9% and 55.4%) than the single-substrate-layer green roof (52.5%). All of the dual-substrate-layer green roofs appeared to be sinks for organics, heavy metals and all forms of nitrogen in all cases, while acted as sources of phosphorus contaminants in the case of heavy rains. In consideration of the factors of water retention, pollution reduction and service life of the green roof, a mixture of activated charcoal and/or pumice with perlite and vermiculite is recommended as the adsorption substrate. The green roofs were able to mitigate mild acid rain, raising the pH from approximately 5.6 in rainfall to 6.5–7.6 in green roof runoff. No signs of a first flush effect for phosphate, total phosphorus, ammonia nitrogen, nitrate nitrogen, total nitrogen, organics, zinc, lead, chromium, manganese, copper, pH or turbidity were found in the green roof runoff. Cost analysis further proved the practicability of dual-substrate-layer green roofs in

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http://dx.doi.org/10.1016/j.scitotenv.2017.03.124

retaining rainwater, and their long-term rainwater runoff quantity and quality performance in urban environments merit further investigation.

1. Introduction

Green roofs have been proposed as an important means to control urban runoff and ease pressure on conventional stormwater infrastructure because of their ability to retain and detain rainwater (Bonoli et al., 2013; Stovin et al., 2012). The runoff retention values observed in previous extensive green roof studies ranged from 15% to 83%, with an average of 57% (Nawaz et al., 2015), and higher average retention values were observed in intensive green roofs (60%–95%) mainly because of the deeper substrates (Beecham and Razzaghmanesh, 2015; Razzaghmanesh and Beecham, 2014; Speak et al., 2013). Moreover, green roofs require no additional space beyond a building's footprint (Stovin et al., 2012; Zhang and Guo, 2013), which is particularly beneficial in densely built urban areas. Rainwater flowing off conventional roofs has been shown to pick up pollutants from rooftops (Lye, 2009), including heavy metals (Lye, 2009); atmospheric depositions, such as SO_2, NO_x and particles (Speak et al., 2012); and organic substances, such as leaves, dead insects, and bird wastes (Chang et al., 2004). Because the green roof retains some of these pollutants (Berndtsson et al., 2009), it has been proposed that the runoff from green roofs has a better water quality than stormwater runoff from conventional roofs (Beck et al., 2011). However, higher nutrient concentrations (nitrogen and phosphorus) have been frequently found in runoff from green roofs compared to runoff from control bare roofs (Gregoire and Clausen, 2011; Monterusso et al., 2004; Razzaghmanesh et al., 2014; Van Seters et al., 2007; Vijayaraghavan et al., 2012). Metals in the runoff have also been a concern because the green roof substrate itself may be a source of metals (Berndtsson et al., 2006; Vijayaraghavan et al., 2012). Additionally, there is the possibility that air pollutants captured by vegetation will eventually leach into the roof runoff (Rowe, 2011).

In addition to the nitrogen and phosphorus amounts contained in the green roof substrate itself, some researchers consider that the compost materials or artificial fertilizers deliberately added to green roofs to promote plant growth are the main cause of nutrient leaching in the runoff (Hunt et al., 2006; Retzlaff et al., 2008; Van Seters et al., 2007). Therefore, to decrease the leaching of nutrients, it would be beneficial if no external nutrient sources were added to the green roof substrate. However, this would lead to a lack of nutrients for plant growth, and the desired dense vegetation cover would not be achieved. To solve this dilemma, Beck et al. (2011) suggested that soil amendments that are able to retain nutrients would be a welcome addition to the green roof industry and showed that the addition of 7% biochar to green roof soil increased water retention and significantly decreased the discharge of total nitrogen (TN), total phosphorus (TP), nitrate (NO_3^--N), phosphate (PO_4^{3-}-P) and organic carbon. Vijayaraghavana and Joshi (2015) incorporated a brown-seaweed (*Turbinaria conoides*) in the growth substrate to enhance the runoff quality from green roofs. Emilsson et al. (2007) recommended the use of encapsulated controlled release fertilizers, which are designed to release nutrients at a pace similar to the nutrient requirements of vegetation, thereby reducing the risk of leaching and fertilization damage to the vegetation. Bus et al. (2016) found that the 2 cm drainage layer made of reactive material Polonite was efficient in reducing PO_4^{3-}-P outflow from green roof substrate by 96%. Wang et al. (2013) and Gong et al. (2014) provided a new type of green roof which is named a dual-substrate-layer extensive green roof, and a commercial controlled-release fertilizer or local grass charcoal soil was used as the nutrient substrate, while a perlite and vermiculite mixed (1:1) substrate was used as the adsorption substrate. Wang et al. (2013) found that dual substrate layer green roofs behaved as a sink for TN, ammonia nitrogen (NH_4^+-N) and chemical oxygen demand (COD), while acted as a source of contaminants for TP. Gong et al. (2014) revealed that the runoff water quality (TN, NH_4^+-N, NO_3^--N and TP) would be improved to some extent with the ageing of dual-substrate-layer green roofs, and that the green roofs also effectively reduced COD and turbidity and neutralised mild acid rain to pH values between 8.25 and 8.63. This study is a follow-up of the two previous studies on dual-substrate layer extensive green roofs (Gong et al., 2014; Wang et al., 2013).

Common green roofs involve five layers: a waterproof and root-resistant membrane, drainage layer, filtering layer, growing substrate (medium) layer and vegetation (Berndtsson, 2010). Previous studies have reported that the substrate properties have a major influence on the water retention capacity (Dunnett et al., 2008; VanWoert et al., 2005) as well as the water purification capacity (Berghage et al., 2008; Hunt et al., 2006) of green roofs. The green roof substrates must be lightweight to meet the weight restrictions of the building roof structures, provide good draining to channel excess water from the roof, have a low organic content to prevent decomposition and collapse of the growing layer, and be capable of supporting good plant growth (Emilsson et al., 2007; Morgan et al., 2013). The substrate in existing green roofs is commonly a single layer composed of a mixture of organic (e.g., garden soil, sawdust, peat, rice husk) and inorganic matter (e.g., slag, vermiculite, sand, expanded perlite) (DB11, 2015; FLL, 2008). The substrate in dual-substrate-layer green roofs in the present study consisted of two layers: (1) the upper layer was an organic nutrition substrate layer to promote plant growth and (2) the lower layer was an inorganic adsorption substrate layer for water retention and pollutant reduction. Based on the requirements for the green roof substrate, activated charcoal, zeolite, pumice, lava, vermiculite and expanded perlite were used as the adsorption substrate. These porous inert materials are generally used as filtering media and adsorbents for environmental protection due to their high sorption capacities.

This study aimed to evaluate the practicability of the dual-substrate-layer extensive green roofs in urban environments, and the specific objectives were to (1) investigate the ability of dual-substrate-layer extensive green roofs, which use porous inert materials (activated charcoal, zeolite, pumice, lava, vermiculite and expanded perlite) as the adsorption substrate, to retain rainwater and reduce pollutant leaching and (2) analyze the cost of the dual-substrate-layer extensive green roofs.

2. Materials and methods

2.1. Experimental setup

Six pilot-scale dual-substrate-layer extensive green roof assemblies, designated G1, G2, G3, G4, G5, and G6, were built on an open flat roof on the Tianjin University campus, Tianjin, China in early June 2015. Each green roof was constructed in a 0.7 m × 0.5 m plastic tray. All trays were placed on a 2° slope to coincide with the drainage slope of the roof. As illustrated in Fig. 1, each dual-substrate-layer green roof consisted of the following layers: a waterproof and root-resistant membrane, a commercial plastic storage drainage plate (25 mm thick), a geotextile filter layer (6 mm thick) preventing the loss of substrate particles, a substrate layer (100 mm thick), a nutrition substrate layer (50 mm thick) and a vegetation layer on the top. Moreover, a geotextile material (0.8 mm thick) was used between the nutrition layer and the adsorption layer to separate the two layers. One traditional single-substrate-layer extensive green roof (G7) was built to be compared with the performance of G1–G6. Except for the substrate layer, G7 roof and all of the six dual-substrate-layer green roofs possessed the same structure. The reference roof is a bituminous membrane roof.