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Effects of recycled glass and different substrate materials on the leachate quality and plant growth of green roofs

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A R T I C L E I N F O

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A B S T R A C T

Green roofs are a key component to building sustainable cities because of their multiple environmental benefits, but without the proper level of care, the leachate from green roofs might contain pollutants and become a new nonpoint pollution source in urban areas. Because its leachate quality is affected by the substrates and plants used, the objective of this study is to evaluate the effects of the substrates and plants with the aim of improving green roof applications. This study tested 3 materials – normal cultivated (C) substrate, commercial green roof (L) substrate, and mixed C and recycled glass (R) substrate – with a focus on using recycled glass materials in the green roof system. Recycled glass is a lightweight and porous material that improves pollutant absorption and water quality purification. Three different types of plants were tested: a sedum, a fern, and a shrub. Therefore, this study evaluated 9 combinations, each with 3 replicates. The differences in the substrates exerted significant effects on the chemical oxygen demand (COD) and phosphorous (P) concentrations. The nitrogen (N) concentrations were affected by differences in both the substrates and the plants. The changes in the observed water quality with time implied that compact substrates and mature plants reduced pollutant concentrations, except for N concentrations, in the outflow. The L substrate contained high levels of nutrients, and the plants grew better in this substrate than in the other two substrates; however, the L substrate also produced higher pollution concentrations. The R substrate, with recycled glass, performed well in the neutralization of acid rain but did not significantly reduce the levels of other pollutants. To enhance the purification ability of the recycled glass, the mixing ratio between the recycled glass and organic substances and the placement in the substrate are important factors.

1. Introduction

Green roofs can produce many environmental benefits, such as urban hydrology improvements, reduced building energy costs, air and noise pollution mitigation, ecological conservation, and beautiful landscape creation (Dunnett and Kingsbury, 2004; Oberndorfer et al., 2007). In addition, green roofs use existing roof space without requiring extra land, allowing potentially widespread application (Peck, 2003; Villarreal and Bengtsson, 2005; Mentens et al., 2006; Dvorak and Volder, 2010). However, the water quality of leachate from green roofs hinders their widespread acceptance. Several factors are related to the leachate quality of green roofs, including the precipitation composition, substrate properties, plants, fertilization, and the roof itself (Teemusk and Mander, 2007; Mentens et al., 2006; Berndtsson, 2010; Rowe, 2011). In general, green roofs consist of substrate and plants and are therefore more likely to generate pollution than bare roofs (Czemiel Berndtsson et al., 2006 ; Hathaway et al., 2008; Carpenter and Kaluvakolanu, 2011). Without proper design and maintenance, runoff from green roofs could become a nonpoint pollution source in urban areas (Chen, 2013).

Green roof leachate quality can be improved by optimizing the substrates and plants used. In Rowe's review paper (2011), high pollution concentrations occur on newly built green roofs, and the concentrations decrease as the plants grow to maturity and the substrates compact with time. Multiple plant species are better at rainwater retention and improving the ecological habitat. Taller plants and plants with deeper roots retain water longer and offer greater runoff reduction (Dunnett et al., 2008; Lundholm et al., 2010). Organic substances are added to the substrates for plant growth but might leach out, causing high organic and sediment loads in the outflow. Many studies have investigated the effects of substrates on leachate quality and have demonstrated that the substrate materials and depth significantly affect it (Teemusk and Mander, 2007; Getter and Rowe, 2009; Alsup et al., 2010).

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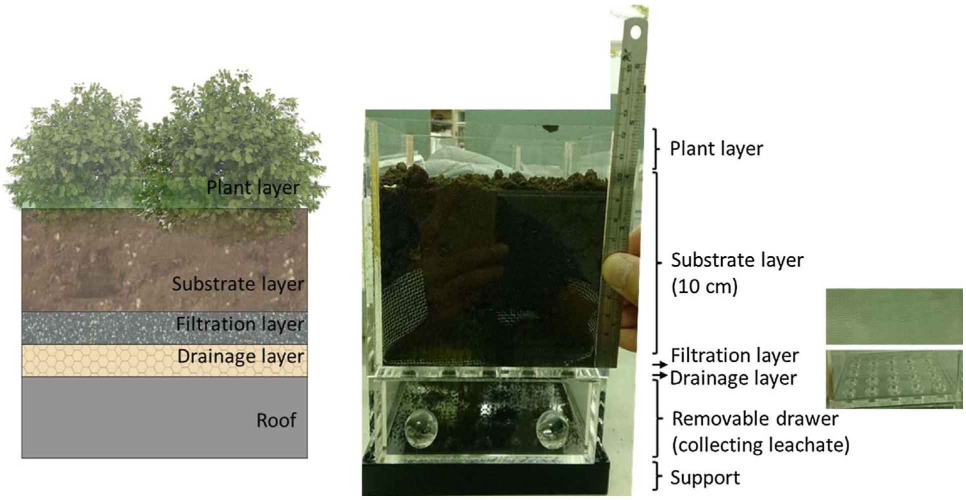

Fig. 1. Sketch of a green roof structure and the photographs of the experimental container.

Substrate components are divided into inorganic and organic substances, both of which can be replaced with recycled materials. For example, compost or green manure can serve as organic nutrients, and abandoned bricks and tiles as inorganic materials. Molineux et al. (2009) used four recycled materials as green roof substrates, including abandoned red bricks, sludge, newspaper, and carbonated limestone. When mixed with certain organic substances, the effects of recycled materials on plant growth vary. These authors concluded that the cost of recycled materials is low, and these materials can be accessed from local markets, benefiting both environmental and economic development. Molineux et al. (2015) subsequently tested 6 recycled lightweight materials and determined the effects of different substrate types and depths on plant growth. The clay substrate supported higher plant coverage and more plant species than other materials. Nagase and Dunnett (2011) tested different ratios of green manures and abandoned red bricks to find the best substrate for plant growth. Graceson et al. (2014) evaluated 9 bricks and 3 tiles with a fixed proportion of 30% green manure to determine their water retention ability and effect on plant growth. Ondono et al. (2014) suggested that the physical, chemical, and biological properties of various artificial materials used in green roofs should be evaluated. These authors tested different ratios of natural loam, bricks, and green manure as substrates and concluded that different substrates affect biological activity, thereby influencing plant growth. Thus, the selection of appropriate substrates is important for green roofs. Bates et al. (2015) tested crushed bricks, building waste, and incinerator bottom ash as substrates and concluded that these materials had the same effect on biomass but that crushed bricks fostered better biodiversity.

Applying recycled materials as substrates is a trend in green roof development. However, previous studies have focused on the effects on plant growth but not the effects on effluent water quality. Substrates have been proven to influence effluent water quality; therefore, the use of recycled materials should consider the effects on not only the plants but also leachate quality. An optimal substrate is expected to benefit plant growth and produce few contaminants. This study aimed to evaluate and compare different substrates, i.e., normal cultivated substrate, special green roof substrate, and mixed recycled glass materials, in terms of their effects on plant growth and water quality. Recycled glass is a lightweight inorganic material that reduces the substrate weight, and its high porosity can provide more space for aeration and water retention. Successful application of recycled materials on green roofs is beneficial for both green roof development and waste resource recycling.

2. Experimental design

2.1. Structure of green roofs

There are two general types of green roofs, extensive and intensive green roofs. The major difference is the depth of the substrate. Extensive green roofs have shallow substrate depths, usually less than 20 cm, whereas intensive green roofs have thicker depths, greater than 20 cm. The thin substrates of lightweight extensive green roofs are suitable for shorter plants, such as herbaceous plants. Intensive green roofs can support shrubs and trees or even horticulture (Rowe, 2011). Although the choice of plant species is more diverse for intensive green roofs than for extensive green roofs, the high weight and frequent maintenance limit the application of intensive green roofs, and extensive green roofs have experienced more widespread application (Chen, 2013). Therefore, the experimental design in this study was based on extensive green roofs.

The basic structure of extensive green roofs, from bottom to top, consists of a drainage layer, filtration layer, substrate layer, and plant layer. Between this structure and the building roof, a root barrier and waterproof barrier are optional but suggested layers according to the building roof condition. In this study, an experimental container is designed (Fig. 1) following the basic structure of green roofs. Its length and width were 15 cm, and the height was 13 cm. The substrate depth was fixed at 10 cm. At the bottom was a removable drawer to receive rainwater flow through the plants and substrates. In this study, 3 substrate materials and 3 plant species, each with 3 replicates, were tested, resulting in a total of 27 ($3 \times 3 \times 3$) experimental units.

2.2. Selection of substrate materials

Three substrate materials were used: normal cultivated (C) substrate, light (L) substrate and a R substrate – mixture of C and recycled glass. The C substrate was a widely used substrate that is easily purchased in Taiwan. The L substrate was a lightweight commercial product specially designed for green roofs and consisted of sandy loam, humus, pottery stone, zeolite, recycled fiber, and activator. The recycled glass material, named SuperSol, is produced by a Japanese company, TRIM CO., LTD, Okinawa, Japan. This recycled glass is widely applied as a filter material in civil engineering, agricultural, drainage, and water purification applications. Because of its high porosity (water absorption $\geqq$30%) and light weight (specific gravity 0.3–0.6), its pollution purification ability is emphasized and has been