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Drought tolerance and thermal effect measurements for plants suitable for extensive green roof planting in humid subtropical climates

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ABSTRACT

This study aims to investigate the physiology, endurance, and environmental thermal regulatory effects of plants suitable for thin layer green roofs, to provide reference for plant selection in future green roofs. Water conservation and drought tolerance experiments are carried out on 31 types of plants in Taichung, in central Taiwan. The drought tolerance of various plants was investigated. Thermal effect experiments were performed on 10 types of plants. The results from this study show that plants suitable for thin layer green roofs resist drought conditions through physiological mechanisms such as succulent foliage, surface cuticles, mucilaginous substances, hairs or spines, and the Crassulacean acid metabolism (CAM). Plants that grew well came from the families *Crassulaceae*, *Euphorbiaceae*, and *Portulacaceae*. When temperature reduction effectiveness was measured in regard to plant height, the best reductions in temperature occurred in 35 cm plants, followed by 15 cm and then 10 cm plants. Green leafed plants have better temperature reduction effects than purple/red leafed plants. The plants suggested in this study are suitable for regions with subtropical climates. Selecting thin layer green roof plants that resist drought, survive well, and decrease temperature effectively can adequately use water resources and realize green building concepts such as ecological friendliness, energy conservation, carbon emissions reduction, and water conservation.

1. Introduction

Swift urban expansion has made green spaces relatively scarce. Anthropogenic heat from motor vehicles, air conditioning, and factory equipment has been increasing relentlessly. Buildings and roads built with materials with the characteristics of high heat retention and absorption, combined with the disruption of wind flows by tall buildings, increase the environmentally stored heat in urban areas and create urban heating [1–3]. Climate record over the last 100 years show that temperatures in Taiwan is increasing at a significantly higher rate than in other parts of the globe and in the oceanic area surrounding Taiwan. The temperature difference between day and night is twice the worldwide average [4,5]. These significant changes indicate that Taiwan is under the influence of a “heat island effect.” The heat island effect creates a vicious cycle of urban energy concentration [4]. The heat from the city cannot be removed, increasing the temperature and the use of air conditioning [6]. Indoor air conditioning and lighting make up 8% of electricity use in Taiwan during the summer. According to statistics from Taiwan Power Company (referred to as Tai-power), electricity consumption from air conditioning increases 6% for every 1° of outdoor temperature rise, which is a significant amount of consumption.

Many researchers have indicated that the most effective way to relive the worsening of urban thermal environments and reduce the heat island effect is to increase the area of greenery [6–9]. Green roofing is a general technique that has been used in many countries around the world [10,11]. It is proven to be effective in both hot and cold climates. Currently, its functions are widely utilized and researched, especially for energy conservation and pollution reduction. “Urban greening” is an effective approach in improving the quality of living environments and reaching the important indicators for ecological harmony: energy conservation and reduction of carbon emissions [12]. In recent years, the Taiwanese government has established many regulations to promote urban greening. For urban land classified for use as parks, green spaces, or children’s playgrounds, the area of greenery must not be lower than 10% of the area for total development. Currently, however, this target ratio has

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not yet been attained in Taiwan. The greeneries in Taiwanese cities are insufficiently planned and unevenly distributed. Urban heating is accelerating, which highlights the problem of insufficient greenery prevalent in Taiwan's urban environment; namely, greenery is insufficient to temper the urban heating environment. Thus, urban greening is the direction of future urban planning in Taiwan.

Countries around the world are promoting green building to solve the problem of insufficient urban green spaces, by creating more horizontal and vertical surface green areas [13]. This will prevent solar heat from entering indoors, lowering indoor temperatures, and reducing the use of air conditioning. Green construction not only lowers temperature and saves energy, but also helps in the control of the microclimate, improves visual scenery, creates an ecological environment for greater biodiversity, slows rainwater runoff, protects buildings, reduces air pollution, reduces noise, relieves the pressure of urban living, and provides horticultural therapy [14]. Buildings receive twice as much solar radiation from rooftops than from vertical surfaces. Thus, rooftop greening is an effective way to reduce temperatures. However, there are some drawbacks in green roofs' construction. When some inappropriate selections of roof planting from materials without scientific rigor, these vegetation types will be led to fragile looking into their shorter life cycles associated with poor maintenance. Improper designs of green roofs likely result in aforementioned problems (i.e., leaking and overweight roofs but unnecessary loading effects) after the substrates have been filled up with soils, these approaches may be redundant in water supply as well as excessive uses of budgets beyond energy saving. There are some inherent limitations while utilizing green roofs with weighted substrates. Due to roof loading limitation for the sake of building safety, a thin-substrate layer roof has been considered to apply currently [12,13,15].

There are insufficient experimental results with reference to Taiwan. Studies conducted in Europe and the United States of their climatic conditions are different from Taiwan, and cannot be used as effective references. Therefore, the goal of this study is to enhance plant selection for rooftop greening by testing the water conservation, drought tolerance, and thermal effects of plants specific to the climate of Taiwan.

2. Materials and methods

2.1. Experimental materials

This study uses planting dishes to cultivate a thin layer green roof plants. Planting dishes are divided evenly with plastic boards. Planting dishes are placed directly upon the rooftop. The choice of drought tolerant plants uses 31 common succulent plants, Sedums, and CAM type plants as the main experimental materials for drought tolerance (Table 1). This includes plant families such as *Commelinaeceae*, *Bromeliaceae*, *Crassulaceae*, *Portulacaceae*, *Asteraceae*, *Aizoaceae*, *Euphorbiaceous*, *Lamiaceae*, and *Liliaceous*.

Nine plants with large morphology differences from the three categories – including ground cover plants, Crassulacean plants, and shrub plants – are selected for concurrent thermal effect observation (Table 2). As different heights and leaf colors are required for the plants in this experiment, plant selection is not limited to the plants in drought tolerance experiments. *Bryophyllum pinnate* was chosen to measure thermal effects from plant height, as it has an easily identifiable height, even internodes length, and even leaf cover. For the measurements of thermal effect due to leaf color, *Ipomoea batata* was selected due to its identical morphologies for leaves of different colors, and its obvious differences in leaf color. Both these plants were chosen for their easily identifiable morphologies, large amount of leaf coverage, and their availability of different leaf colors. All plants were planted in planting dishes with 100% coverage. Thermal effects were measured after allowing the plants to grow stably on the rooftop environment for a certain period.

2.2. Experimental environments

With an outdoor experimental environment of high average humidity of $71.5 \pm 3.4(\%)$, the tableland is located in a subtropical monsoon region with relative dried autumn-winters and warm summers. August temperatures average $28.7\,^{\circ}$C, and November temperatures average $22\,^{\circ}$C. Annual average precipitations in dried months ranged dramatically from 12.4 mm to 818.8 mm. The solar radiation hours were detected at 169.9 ± 29.8 h/month. The experimental location was at the top floor of an eight floor building free of shade from surrounding buildings. Wind speed was detected at an average of 6.9 ± 2.1 m/s. A thin layer of green roof plants was planted in this environment for experiments in un-watered drought tolerance and thermal effects.

2.3. Experimental method for drought tolerance

Thirty-one types of plants were planted in separated planting dishes. After 3 months of stable growth with regular watering, drought experiments followed by halting all watering by humans and leaving the plants to grow under natural environment conditions on the rooftop. The period of experimentation was from August 1, 2009 to December 1 2009; a total of 123 days, for roughly 4 months. The rainfall information below came from the Central Weather Bureau.

The aim of this study was to investigate the tolerance for dehydration of different types of plants, and to use the observation results to determine their drought tolerance. Photographic records were kept to continuously observe plant growth conditions and survival rates. The results were analyzed visually, and separately discussed in the following two groups:

i. Plants are classified into one of five categories of growth to analyze drought tolerance. The categories included normal growth, stunt growth, obviously wilted apical leaves only, and dead.
ii. Days of normal growth for plants were graphed to visually represent the drought tolerance capabilities of different plants.

2.4. Thermal effect experimental methods

This study sought to understand the temperature reduction benefits of different plant characteristics, individual height, and leaf color. The capabilities for environmental heat modulation for different plants were analyzed by actual measurement and comparisons. The test site was located on a rooftop of an 8 storey building, without shade from surrounding buildings. The plants could have been influenced by meteorological factors such as strong wind, cloud cover, and solar radiation. These factors were not controlled, so that the observational data could represent realistic scenarios.

2.4.1. Experimental apparatus and calibration

In this study, thermocouple wire and infrared thermal imagers were used concurrently in prescribed positions for measurement of plant characteristics in the thermal effect experiment, to investigate the influence of plant characteristics on environmental thermal regulation. The equipment used in this study included an infrared thermal imager, a K type thermocouple wire, and a CR 800 data recorder.

All objects above 0 K ($-273.15\,^{\circ}$C) emitted infrared rays are formed within the range of electromagnetic spectrum. According to Planck's law, the certain amount of energy emitted by a black body is determined as a function of frequency by its wavelength of