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Impact of climatic conditions on the thermal effectiveness of an extensive green roof☆

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ABSTRACT

The density of urban development has been the source of a number of environmental issues, and in urban areas with large quantities of stereoscopic space, roof greening has become an important strategy for land compensation and environmental quality improvement. In particular, with the intensification of urban heat island and the global warming phenomena, the effective regulation of the microclimate by building a green roof becomes more attractive. Because a green roof is closely related to the climate and the environment, the main purpose of this study is to explore the impact of climatic conditions on the thermal effectiveness of an extensive green roof. The experimental cases of an extensive green roof were individually established in urban areas with both sub-tropical and tropical island climates, and synchronous observations were made. The research results show that it can reduce the increase of outdoor temperature by approximately 42% and the increase of the indoor temperature by 8% during the daytime. During the night, it can maintain 17% of the temperature in the outdoor environment, stabilizing the temperature change. The thermal effectiveness of an extensive green roof is closely related to the climate. The daytime cooling effectiveness was relatively high in the tropical island climate in summer, and the nighttime insulation effectiveness was more pronounced in the sub-tropical climate. Rainfall reduced the thermal effectiveness of an extensive green roof.

1. Introduction

Green roofs have been built and used for thousand years. Green roofs not only provide recreational services but also provide substantial efficacy for ecosystem services, including the regulation of the micro-climate, management of storm waters, noise absorption, air purification, and wildlife habitat provision. In recent years, with the increasing global warming phenomenon, major metropolitan areas in many countries in the world have attached considerable importance to greenhouse gas emissions and the impact of the change in land use on temperature, especially the urban heat island phenomenon, which has direct and indirect impacts on the health and quality of the living environment for urban residents. Stone et al. [1] investigated 50 U.S. metropolitan areas, analyzed the behaviors of the major cities in response to climate change, and classified them into three categories, increasing the urban planting and the green coverage, increasing the urban albedo, and improving the efficiency of energy use. In the cities of Boston, Chicago, Los Angeles, New York, and Portland, the urban heat island phenomenon was relieved by increasing the city green coverage with roof greening and tree planting. Related research has shown that an increase in planting and green coverage is the most effective way to mitigate the urban heat island phenomenon [2,3]. Furthermore, the vegetation had a dramatically influence on indoor thermal condition [4]. In urban areas with a large amount of stereoscopic space, the green roof has become one of the main strategies used to increase the urban green space for the government and relevant organizations.

Based on the substrate depth, there are two types of green roof: intensive and extensive green roofs. An intensive green roof has a deeper substrate layer, which can support large-scale plants and facilities, providing the green roof with a richer sense of design and beauty, i.e., a roof garden. An extensive green roof has a thinner substrate layer, with the advantages of convenience, easy operation, low maintenance requirement, and no load consideration [5]. With the trend for energy saving, an extensive green roof is currently the main type promoted in the major cities of the world. In Germany, the U.S., Canada, Singapore, Japan, and other countries, governments have developed a variety of norms and incentives and

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technical services to promote roof greening [6]. Germany is regarded as the birthplace of the modern green roof. The Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL) has promoted the extensive green roof since the 1970s. With continuous research and technology development, the area of constructed green roof in Germany is now more than 1 million square meters. In addition, the FLL green roof guidelines has been widely adopted by many countries. The U.S. has also started to focus on green roof construction in recent decades. Because of a shortage of technical information for green roof construction and quantitative effectiveness data, the U.S. usually follows the European technical specifications [7]. The development of green roof in Taiwan can be traced back to 1978. It was actively promoted by the Taipei City Government's Bureau of Construction (now the Department of Economic Development). Initially, the residents in Taipei were encouraged to build a "roof garden". Due to the intensive maintenance requirement, the action was ceased. Since then, with the public recognition for the value of green space and increased attention to energy saving and carbon reduction issues, the extensive green roof has become one of the most preferred alternatives to increase the green coverage. In recent years, the municipalities have actively promoted roof greening with building bulk incentives [6]. As is the case with many other countries and cities, the promotion and implementation of green roofs in Taiwan requires local quantitative data and construction technology, thereby triggering the academia in Taiwan to pursue green roof research [8,9].

Reviewing the research related to green roofs, the research topics can be roughly grouped into two categories, the study of substrate and plant material and the study of the environmental benefits of green roofs. The studies on substrate and plant material dominate the research field. Because a green roof is constructed on the outermost layer on the top of the building, it is considered a layer of the building structure [10]. Unlike other structures, the green roof layer is a structure of living body, and the plant layer is the living structure. The success of the plant growth is related to the substrate composition. In the case of the extensive green roof, the substrate layer is relatively thinner, thus the environment to support the plant growth is relatively poor. Many studies have focused on the substrate composition and the plant selection for extensive green roofs [8,11–13].

In terms of environmental benefits, many scholars have recently become involved in research in this field. The review of the studies of green roofs shows that the effectiveness of energy-saving and cooling accounted for the majority of the studies, indicating the importance of green roofs on the temperature regulation of buildings. However, with different climates, plant materials, and construction conditions, the effectiveness may vary in studies performed in Europe, North America, and other regions. Many studies have concluded that a regional study is needed to demonstrate the benefits of green roofs in a specific district [14,15].

Based on the importance of green roofs in regulating building temperatures and the impact of climate differences on thermal effectiveness, in this study, the thermal effectiveness of an extensive green roof in different climatic conditions were investigated. Extensive green roofs were built in Taipei (sub-tropical island climate) and Chiayi (tropical island climate). The micro-climate was synchronously monitored in the long term. The similarities and differences of the thermal effectiveness at both sites at different times in the day, in different weather conditions, and during different seasons, as well as the impact of these factors, were analyzed to cumulate quantitative experimental data and to provide a reference for related future research in the advancement of extensive green roof technology.

2. Literature review

Green roofs have multiple benefits for humans and the environment [16], which have been described in many promotional brochures. The presence and intensity of its effectiveness, however, still need to be quantified and assessed. The study on the assessment of the environmental benefits of green roof is another main research topic, second only to research on the substrate and plant material.

The study of the assessment of the environmental benefits of green roof includes the assessment of energy-saving and cooling effectiveness [17–20], cost-benefit analyses [21,22], and storm water management [17], in which the number of the studies on energy-saving and cooling are the largest.

2.1. Energy saving

In the studies related to the energy-saving effectiveness of green roofs, the savings in air conditioning in summer and the reduction of heater usage in winter were explored. Because of the different climate background and different building materials in different regions, the energy-saving effectiveness varied from study to study.

Sfakianaki et al. [19] investigated the energy saving of a green roof system on the residential buildings in Athens, Greece. The results showed that a green roof in the Mediterranean climatic conditions could only provide limited insulation effect for most buildings. In contrast, a green roof was able to effectively reduce the cooling load by approximately 11% for thermostatically controlled buildings. The study also found that a green roof improved heat comfort in summer for the ordinary buildings, with a maximum expected temperature drop of approximately 0.6 °C between the roof surface and interior. Santamouris et al. [23] investigated the energy and environmental performance of a green roof system installed in a nursery school building in Athens, Greece. The study concluded that a green roof could significantly decrease the electricity consumption used in the summer for air-conditioning by 6–19% for the entire building and by 12–87% for the top floor alone; however, it did not provide any savings in heating. The study on the energy-saving effectiveness of a green roof for the commercial buildings in Athens, Greece, showed that a green roof reduced the electricity consumption for air-conditioning in summer approximately 40%; however, the results showed no significant savings in heating [24].

Different levels of insulation of the roof slab resulted in different cooling effectiveness of the green roof. Niachou et al. [25] and Theodosiou [26] analyzed the energy-saving effectiveness of a green roof with varying thermal transmittance U-values using numerical simulations. Their study concluded that as the degree of insulation of the roof slab decreases, the effectiveness of the energy-saving after greening increases. Castleton et al. [5] reviewed the existing literature to specifically explore the largest energy-saving effectiveness derived from roof greening. They concluded that old buildings with poor insulation received the largest benefit from a green roof. The annual energy usage of modern buildings, built with high standard insulation layer specifications, gained little from the construction of a green roof.

To assess the energy-saving effectiveness, Sailor [10] proposed the green roof energy balance model, which was integrated into the EnergyPlus building energy simulation program, to assess the energy usage of a building with a green roof. The study found that the efficiency of energy use is closely related to the characteristics of the green roof and the climate condition of the building location.

2.2. Cooling

Cooling is one of the most direct indicators used to assess the energy-saving efficiency of a green roof. Many studies have