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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 investigated the effectiveness of the green roof by measuring the change in cooling. Different regions, greening styles, plant materials, and substrate formulations may all affect the cooling effectiveness [27,28].

Wong, Tan, & Chen [20] studied the temperature before and after greening for the green roof of a Singapore building. The results showed that the green roof after greening demonstrated significantly reduced surface temperature, especially for the roof with high plant coverage, which resulted in a maximum temperature difference of approximately 18 °C. Different plants may also result in different levels of effectiveness. As the amount of the coverage increased, the magnitude of the temperature change (decrease) also increased. The study in Hong Kong showed that the heat storage of the non-greening roof was higher than that of the green roof by 75% [29]. In hot and humid Reunion Island, India, the coverage of an extensive green roof was shown to reduce the temperature on the roof surface by a maximum temperature difference of approximately 38 °C, and the heat flow through the roof was reduced by approximately 51–63% [30]. The study on the thermal effectiveness of green roofs in northern and central Italy also showed that a green roof could reduce the daily heat loss through the roof [17]. Tang & Yang [31] proposed that solar radiation, air temperature, and wind speed have a positive impact on reducing the internal surface temperature but that relative humidity and rainfall are negatively correlated with the decrease of the internal temperature. A green roof significantly delayed the response of the roof to the radiant heat of the sun and exhibited very good thermal inertia.

With the growth of the urban heat island phenomenon, many cold roof approaches have been developed. Comparisons of the cooling effectiveness between the green roof and other types of cool roof have also been made.

D'Orazio et al. [32] explored the effectiveness of the green roof and other types of cool roof with a high degree of insulation in an experimental house near Ancona, Italy. The results showed that the installation of a green roof could reduce the surface temperature in summer and stabilize the daily variation of temperature. Teemusk & Mander [18] studied the temperature changes with a green roof, a turf roof, a modified bituminous membrane roof, and a steel sheet roof in the city of Tartu, Estonia. The research results showed that the temperatures in summer were similar for the green roof (100 mm) and the turf roof (150 mm), and the high temperature on the surface did not significantly affect the temperature under the substrate layers. The temperature amplitude beneath the substrate layer compared to the surface of uncovered roof showed an average temperature difference of approximately 20 °C. In the autumn and spring, the temperature of the substrate layer for the turf roof was higher than the temperature of the substrate of the green roof. In the winter, the temperature below the substrate of the green roof was higher than the surface temperature of the non-greening roof.

3. Methods

In this study, the experimental sites for long-term and continuous measurement of the thermal effectiveness of an extensive green roof were constructed. The site construction, the experimental methods, and the data collection are described below.

3.1. Experimental sites and experimental design

3.1.1. Experimental sites

To investigate the thermal effectiveness of an extensive green roof under different climatic conditions, roofs in the urban areas of Taipei and Chiayi were selected for the experimental observations. Taipei (25°02′ N, 121°30′ E) has a sub-tropical island climate, with an average annual temperature of 22.7 °C and annual rainfall of 1758.6 mm; Chiayi (23°28′ N, 120°26′ E) has a tropical island climate, with an average annual temperature of 23.1 °C and annual rainfall of 1021.7 mm [33].

The criteria for experimental roof selection included a flat roof that was not under the shade of tall buildings, that was closed to the general public (to reduce the impact of humans), and that had the largest possible contiguous area. The roof of the Landscape Architecture Building of National Taiwan University was selected as the experimental site in Taipei, and the roof of the building of the Department of Agriculture and Landscape Architecture in National Chiayi University was selected as the experimental site in Chiayi. The two roof slabs were insulated, the roof slab in Taipei was built with foam concrete ($U = 0.75$ W/m^2 K) and the roof slab in Chiayi was built with insulating concrete ($U = 0.74$ W/m^2 K). Beneath the two roofs are classrooms and facility offices conditioned with air conditioners. In spring, summer and autumn, the air conditioners operate in daytime on weekdays and turn off on weekends. In winter, the air conditioners turn off all day.

To avoid the influence of the shade of the parapet, water towers, and other appendages of the building, the shadows on the roof of the buildings were analyzed for the two experimental sites in Taipei and Chiayi. The areas with no shadow influence were chosen as the experimental areas.

3.1.2. Experimental design

Identical extensive green roofs were installed in the experimental areas of both of the roofs in Taipei and Chiayi. In each experimental area, a reference point without shadow influence from the extensive green roofs was chosen for comparison purpose.

Imitating the construction method of extensive green roofs, the experimental roofs included protective pads, a reservoir drainage board, a permeable pad, a substrate layer, and a planting layer (bottom-up). Ten modules of extensive green roof with substrate thickness of 10 cm and totally sized 2.5 m^2 were constructed for each study roof. The substrate formulation followed the substrate formula proposed by the Taipei Hsi Liu Environmental Greening Foundation [34], using a ratio of peat soil: coir: perlite: sand of 6:1:1:2. During the experimental period, the moisture management was performed by an automatic sprinkler system, providing 3 min of automatic sprinkling from 06:00 am – 06:03 am daily. (Preliminary tests showed that approximately 3 min of continuous watering with the sprinkler system was required to reach the full capacity of the substrate). The selected plant layers included mainly the plant species commonly used in extensive green roof in Taiwan. The plant species selected were *Torenia concolor*, *Ixora williamsii*, *Ruellia brittoniana*, *Mesona chinensis*, *Asporagus densiflorus*, *Acalypha wilkesiana*, *Evolvulus alsinoides*, *Trachelospermum asiaticum*, *Liriope spicata*, and *Graptopetalum paraguayense*.

3.2. Measurement data and instrument settings

To investigate the thermal effectiveness of the extensive green roof on the building, the outdoor and indoor temperatures were monitored. The temperature of the roof surface below the module covering was defined as the outdoor module temperature. The surface temperature beneath the corresponding indoor ceiling slab was defined as the indoor module temperature. The temperature of outdoor surface at the reference point was the outdoor reference temperature, and the surface temperature beneath the corresponding indoor ceiling slab was the indoor reference temperature (Fig. 1). The two experimental fields were monitored in a synchronous manner. The data collected included the outdoor module temperature, the outdoor reference temperature, the indoor module temperature, and the indoor reference temperature.

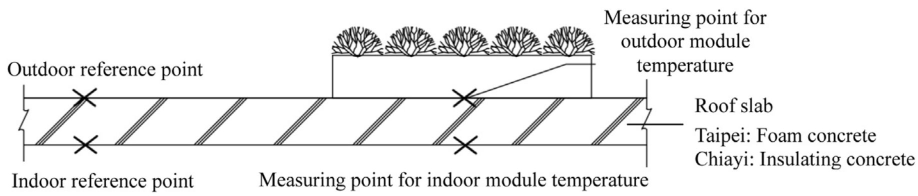

Fig. 1. The schematic diagram of the positions of measurement.

Thermocouple wires (Type T, accuracy: ± 0.5 °C@ −40 °C–125 °C) were used to measure the outdoor module temperature, the indoor module temperature, and the indoor reference temperature. The outdoor reference temperature was measured with an SI-111 Precision Infrared Radiometer (Campbell Scientific, Inc., Logan, UT; accuracy: ±0.2 °C @ −10° to 65 °C, ±0.5 °C @ −40° to 70 °C; precision: ±0.05 °C @ −10° to 65 °C, ±0.1 °C @ −40° to 70 °C), which was mounted perpendicular to the surface of the reference point and had a distance about 20 cm.

Both the thermocouple wires and the SI-111 Precision Infrared Radiometer were connected to a CR-1000 automatic recorder (Campbell Scientific, Inc., Logan, UT), which was set to record the measured values every 5 min.

4. Results

Both experimental sites were monitored continuously and synchronously for 11 months between 2011/02/01 and 2011/12/31. The monitoring results and the thermal effectiveness are discussed in the following sections.

4.1. The monthly average temperature difference at different times of the day

To analyze the differences in the thermal effectiveness at different times of day, the thermal effectiveness was calculated by subtracting the module temperature from the reference point and averaging the thermal effectiveness of a time period for each month. The Taipei outdoor temperature difference, the Chiayi outdoor temperature difference, the Taipei indoor temperature difference, and the Chiayi indoor temperature difference of each period in each month were plotted as the graph for the changing trend of the thermal effectiveness for different periods of time, as shown in Fig. 2.

The monitoring data for the 11-month period showed that the thermal effectiveness was different in Taipei and Chiayi. The thermal effectiveness in Chiayi was greater than that in Taipei. The change of outdoor thermal effectiveness of the extensive green roof has an inverted U shape, demonstrating a cooling effect during the daytime and an insulating effect at night. The thermal effectiveness varied for the different months, showing that different seasons can affect the performance of the thermal effectiveness of the extensive green roof.

In addition, the outdoor thermal effectiveness was much larger than the indoor thermal efficiency in daytime, and the outdoor thermal effectiveness was the largest at noontime. For the daytime indoor thermal effectiveness, taking advantage of the barrier effect of the building slab, the temperature increase at the indoor reference point was delayed, and the increase in the indoor module temperature was delayed even more. Therefore, the daytime cooling effectiveness was delayed until the afternoon when the temperature difference reached the maximum. The positive difference between the indoor reference point and the indoor module temperature

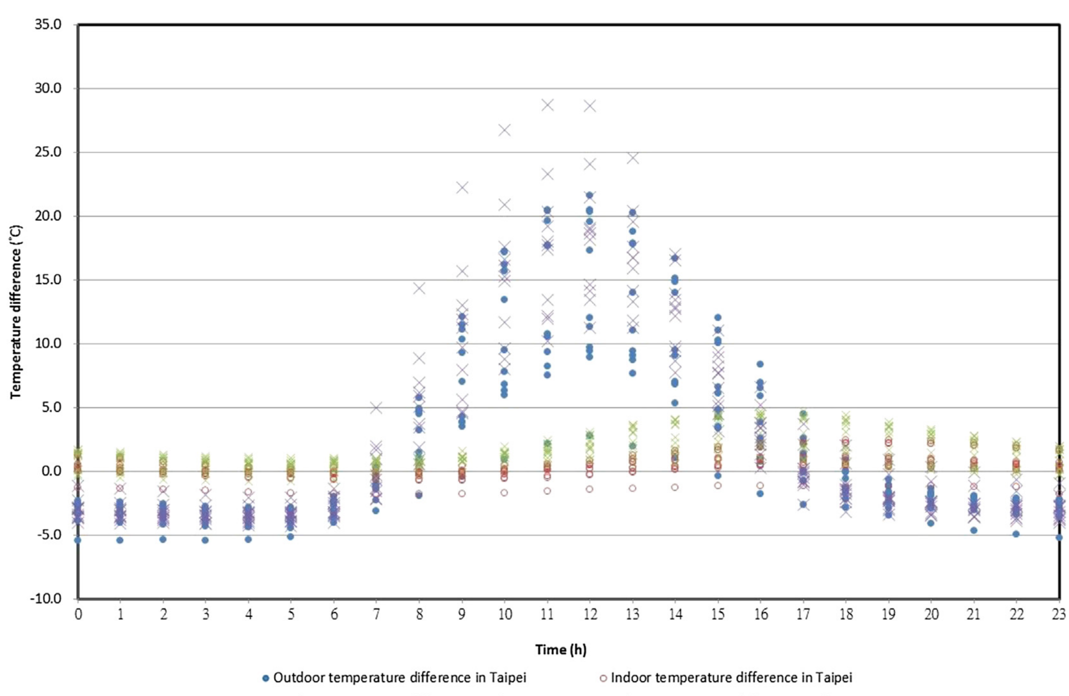

Fig. 2. Comparison of time and the temperature difference between module and reference point for Taipei and Chiayi.

persisted until the night, indicating that the heat absorbed at the reference point of the slab during the day continued to pass through to the slab below the extensive green roof covering and that equilibrium was reached in the early morning (Fig. 2).

Further, the observation data were divided into two groups: data measured on rainless days and data measured on rainy days. The rainy days were those days with daily accumulated precipitation over 0.1 mm recorded by the weather stations, Taipei Weather Station and Chiayi Weather Station, nearby the two experimental sites. The results after the removal of the observation data obtained on the rainy days are shown in Fig. 3.

After the removal of the influence of rainfall, the trend of the thermal effectiveness was substantially unchanged but the strength of the thermal effectiveness was significantly enhanced, indicating that weather affects the performance of the thermal effectiveness of the extensive green roof (Fig. 3).

4.2. Outdoor thermal effectiveness

According to the temperature change tendency of the respective periods shown in Figs. 2 and 3, the outdoor and indoor cooling effects of the extensive green roof present different effectiveness peaks. An outdoor cooling peak appears at noontime, from 10:00 am – 2:00 pm. Thus, an analysis for the period of 10:00 am – 2:00 pm as the maximum cooling period of the extenisve green roof for the outdoor environment was performed. Similarly, the period of 01:00 am – 5:00 am at night was used as the maximum insulation period of the extensive green roof.

Due to the difference in the intensity of temperature difference between Figs. 2 and 3, this study further analyzed the thermal effectiveness of the extensive green roof on the rainless and rainy days.

4.2.1. Thermal effectiveness at noontime

On the rainless days, the noontime temperature at the outdoor reference point was much higher than the module temperature at noontime, indicating a significant cooling effect of the extensive green roof on the outdoor temperature.

Table 1
The *t*-test analysis of outdoor thermal effectiveness at noontime on the rainless days.

Temperature (°C)		Reference point	Module	Temperature difference	Difference of thermal effectiveness between the two sites
Spring	Taipei	38.1	20.3	17.8 ***	−0.5 n.s.
	Chiayi	43.3	26.0	17.3 ***	
Summer	Taipei	51.7	29.2	22.5 ***	2.6 **
	Chiayi	57.7	32.2	25.1 ***	
Autumn	Taipei	40.0	24.7	15.3 ***	3.8 ***
	Chiayi	46.7	27.6	19.1 ***	
Winter	Taipei	29.3	17.2	12.1 ***	0.5 n.s.
	Chiayi	32.2	19.6	12.6 ***	
Average	Taipei	40.9	23.5	17.4 ***	1.3 **
	Chiayi	45.3	26.6	18.7 ***	

Note 1: The analysis period was 10:00 am – 2:00 pm.
Note 2: *** refers to $p < 0.001$, ** refers to $p < 0.01$, and n.s. refers to no significant difference.

The noontime outdoor cooling effectiveness ranged from 12.1 °C to 22.5 °C in Taipei and from 12.6 °C to 25.1 °C in Chiayi. Both locations showed the greatest degree of cooling effectiveness in summer and lowest cooling effectiveness in winter. Comparing the reference points and the module temperatures in the two places, the measured temperatures of Chiayi were higher than those of Taipei in all seasons. Further comparison of the differences in the cooling effectiveness between the two places showed that, in the summer and autumn, the noontime cooling effectiveness of Chiayi was significantly higher than that of Taipei. In the summer, the cooling effectiveness was approximately 43.8% in Chiayi and 43.5% in Taipei. In the autumn, the cooling effectiveness was approximately 40.9% in Chiayi and 38.3% in Taipei. The analyzed results showed that as the temperature increases, the cooling effectiveness of the extensive green roof becomes more significant (Table 1).

Affected by rainfall, the outdoor noontime temperature of the reference point was significantly decreased at both the Taipei and Chiayi sites, with a larger drop in Taipei (Tables 1 and 2). However, the outdoor temperature of the reference point was still

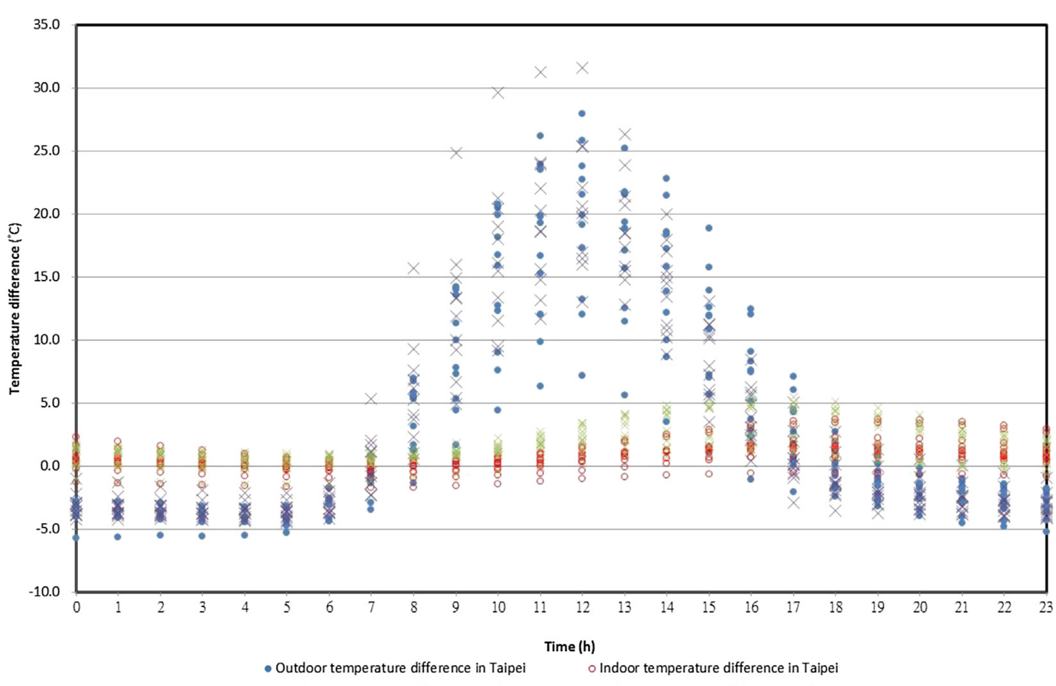

Fig. 3. Comparison of time and the temperature difference between module and reference point on the rainless days for Taipei and Chiayi.

Table 2
The *t*-test analysis of outdoor thermal effectiveness at noontime on the rainy days.

Temperature (°C)		Reference point	Module	Temperature difference	Difference in thermal effectiveness between the two sites
Spring	Taipei	26.8	21.0	5.8 ***	4.9 ***
	Chiayi	35.5	24.8	10.7 ***	
Summer	Taipei	43.1	29.5	13.6 ***	3.5 ***
	Chiayi	47.4	30.3	17.1 ***	
Autumn	Taipei	31.0	24.5	6.5 ***	4.7 ***
	Chiayi	38.5	27.3	11.2 ***	
Winter	Taipei	18.2	17.2	1.0 *	5.5 ***
	Chiayi	24.7	18.3	6.5 ***	
Average	Taipei	30.6	23.5	7.1 ***	5.9 ***
	Chiayi	39.8	26.8	13.0 ***	

Note 1: The analysis period was 10:00 am – 2:00 pm.
Note 2: *** refers to $p < 0.001$, and * refers to $p < 0.05$.

significantly higher than the module temperature, indicating that the noontime cooling effect was still significant in rainy days (Table 2).

On the rainy days, the noontime outdoor cooling effectiveness ranged from 1.0 °C to 13.6 °C in Taipei and from 6.5 °C to 17.1 °C in Chiayi (Table 2). Compared to the rainless days, the noontime cooling effectiveness was decreased significantly by rainfall, and the difference in the thermal effectiveness between the two sites becomes much greater when influenced by rainfall. In Taipei, increased rainfall levels led to a greater drop in roof temperatures; therefore, the cooling effectiveness of the extensive green roof was therefore reduced (Tables 1 and 2).

4.2.2. Thermal effectiveness at nighttime

On the rainless days, the extensive green roof showed significant insulation at nighttime, with the nighttime outdoor insulation effectiveness ranging from 3.4 °C to 4.6 °C in Taipei and from 3.1 °C to 3.8 °C in Chiayi.

Comparing the outdoor reference points and the module temperatures at nighttime at the two locations, the measured temperatures at Chiayi were higher than those at Taipei in all seasons. Further comparison of the differences in the nighttime thermal effectiveness between the two sites showed that in the summer and spring, the nighttime insulation effectiveness at Taipei was significantly higher than that at Chiayi.

The comparison of the nighttime temperature changes in the spring and summer between the two sites showed that the spring temperature at Taipei was far below that at Chiayi. In particular, the temperature difference at the reference point was greater and the module temperature change was relatively small, suggesting that the extensive green roof had a greater insulating effect at nighttime, accompanied by a greater temperature change (Table 3).

As depicted by the analyzed results, the water from the rainfall caused a slight increase in the nighttime temperature at the reference point, but the module temperature did not change much. Compared to the rainless climate, the nighttime insulation effectiveness of the extensive green roof on the rainy days is reduced, but the insulation effectiveness was still greater than 2.0 °C (Table 4). On average, the effect of rainfall was to reduce the difference of the thermal effectiveness between the two sites at night (Tables 3 and 4).

Table 3
The *t*-test analysis of outdoor thermal effectiveness at nighttime on the rainless days.

Temperature (°C)		Reference point	Module	Temperature difference	Difference in thermal effectiveness between the two sites
Spring	Taipei	16.3	20.9	−4.6 ***	1.2 ***
	Chiayi	23.1	26.5	−3.4 ***	
Summer	Taipei	25.8	29.7	−3.9 ***	0.8 ***
	Chiayi	29. 6	32.7	−3.1 ***	
Autumn	Taipei	21.6	25.0	−3.4 ***	−0.2 n.s.
	Chiayi	24.3	27.9	−3.6 ***	
Winter	Taipei	13.5	17.6	−4.1 ***	0.3 n.s.
	Chiayi	16.4	20.2	−3.8 ***	
Average	Taipei	20.0	23.9	−3.9 ***	0.4 ***
	Chiayi	23.6	27.1	−3.5 ***	

Note 1: The analysis period was 1:00 am – 5:00 am.
Note 2: *** refers to $p < 0.001$, and n.s. refers to no significant difference.

Table 4
The *t*-test analysis of outdoor thermal effectiveness at nighttime on the rainy days.

Temperature (°C)		Reference point	Module	Temperature difference	Difference in thermal effectiveness between the two sites
Spring	Taipei	18.4	21.4	−3.0 ***	0.3 *
	Chiayi	23.2	25.9	−2.7 ***	
Summer	Taipei	25.8	29.8	−4.0 ***	1.3 ***
	Chiayi	28.2	30.9	−2.7 ***	
Autumn	Taipei	22.3	24.7	−2.4 ***	−0.6 **
	Chiayi	24.9	27.9	−3.0 ***	
Winter	Taipei	14.9	17.5	−2.6 ***	−0.1 n.s.
	Chiayi	16.3	19.0	−2.7 ***	
Average	Taipei	20.7	23.8	−3.1 ***	0.3 **
	Chiayi	24.7	27.5	−2.8 ***	

Note 1: The analysis period was 1:00 am – 5:00 am.
Note 2: *** refers to $p < 0.001$, ** refers to $p < 0.01$, * refers to $p < 0.05$, and n.s. refers to no significant difference.

4.3. Indoor thermal effectiveness

According to the temperature trend for each period shown in Figs. 2 and 3, the extensive green roof showed an indoor cooling peak in the afternoon, between 2:00 pm – 6:00 pm. Thus, the analysis was performed using the period from 2:00 pm – 6:00 pm as the maximum cooling period of the extensive green roof for the indoor environment; similarly, the analysis was performed using the period from 01:00 am – 5:00 am as the maximum insulation period of the extensive green roof. The indoor thermal effectiveness of the extensive green roof was further analyzed on the rainless and rainy days.

4.3.1. The thermal effectiveness in the afternoon

The indoor temperatures of all the measured points in Chiayi were higher than those in Taipei. The indoor thermal effectiveness

Table 5
The *t*-test analysis of indoor thermal effectiveness in the afternoon on the rainless days.

Temperature (°C)		Reference point	Module	Temperature difference	Difference in thermal effectiveness between the two sites
Spring	Taipei	24.0	23.0	1.0 *	3.2***
	Chiayi	30.7	26.5	4.2 ***	
Summer	Taipei	33.9	31.4	2.5 ***	1.3 ***
	Chiayi	36.4	32.6	3.8 ***	
Autumn	Taipei	27.8	26.5	1.3 ***	0.3 n.s.
	Chiayi	29.6	28.0	1.6 ***	
Winter	Taipei	19.7	19.1	0.6 n.s.	2.9 ***
	Chiayi	23.2	19.7	3.5 ***	
Average	Taipei	27.1	25.7	1.4 ***	1.8 ***
	Chiayi	30.2	27.0	3.2 ***	

Note 1: The analysis period was 2:00 pm – 6:00 pm.
Note 2: *** refers to $p < 0.001$, * refers to $p < 0.05$, and n.s. refers to no significant difference.

Table 6
The *t*-test analysis of indoor thermal effectiveness in the afternoon on the rainy days.

Temperature (°C)		Reference point	Module	Temperature difference	Difference in thermal effectiveness between the two sites
Spring	Taipei	22.7	22.5	0.2 n.s.	2.2 ***
	Chiayi	27.0	24.6	2.4 **	
Summer	Taipei	32.1	31.3	0.8 ***	2.2 ***
	Chiayi	33.0	30.0	3.0 ***	
Autumn	Taipei	26.2	25.8	0.4 n.s.	0.0 n.s.
	Chiayi	27.8	27.4	0.4 n.s.	
Winter	Taipei	17.4	18.2	−0.8 **	3.0 ***
	Chiayi	20.1	17.9	2.2 ***	
Average	Taipei	25.1	24.9	0.2 n.s.	2.0 ***
	Chiayi	28.8	26.6	2.2 ***	

Note 1: The analysis period was 2:00 pm − 6:00 pm.
Note 2: *** refers to $p < 0.001$, ** refers to $p < 0.01$, and n.s. refers to no significant difference.

showed that the extensive green roof can significantly lower the indoor temperature, except that the winter indoor thermal effectiveness in Taipei is not significant, as measured by the *t*-test. The indoor cooling effectiveness ranged from 1.0 °C to 2.5 °C in Taipei and from 1.6 °C to 4.2 °C in Chiayi. Comparing the indoor cooling effectiveness at the two sites, the effectiveness at Chiayi was, in most cases, significantly higher than that at Taipei (Table 5).

On the rainy days, the indoor temperatures of the reference point and module were decreased for both locations and the indoor cooling effectiveness was reduced.

Overall, on rainy the days, the indoor cooling effectiveness of the extensive green roof ranged from 0.8 °C to 3.0 °C, and the indoor cooling effectiveness in Chiayi was higher than that in Taipei. In the winter, the effect of indoor insulation was observed in Taipei (Table 6).

4.3.2. The thermal effectiveness at nighttime

On the rainless days, the nighttime temperatures measured at all points in Chiayi were higher than those in Taipei. Comparing the temperature difference between the reference point and module at both Taipei and Chiayi, the nighttime indoor temperature at the reference point was similar to the module indoor temperature. However, the indoor cooling effectiveness in the spring and winter was still significant in Chiayi, whereas a significant indoor cooling effect in the summer was shown in Taipei (Table 7).

Compared with the rainless days, the nighttime indoor thermal effectiveness of the extensive green roof showed a weakening trend on the rainy days. Affected by the rainfall, the nighttime indoor cooling effectiveness at Chiayi decreased in winter, and the indoor cooling effectiveness was not significant in the spring. At Taipei, the nighttime indoor cooling effectiveness was not significant in summer. However, the nighttime indoor insulation effectiveness was enhanced on the rainy days (Table 8).

Table 7
The *t*-test analysis of indoor thermal effectiveness at nighttime on the rainless days.

Temperature (°C)		Reference point	Module	Temperature difference
Spring	Taipei	22.2	22.1	0.1 n.s.
	Chiayi	27.1	26.0	1.1 **
Summer	Taipei	31.6	30.7	0.9 ***
	Chiayi	32.6	32.5	0.1 n.s.
Autumn	Taipei	26.0	26.1	−0.1 n.s.
	Chiayi	27.6	27.7	−0.1 n.s.
Winter	Taipei	18.0	18.3	−0.3 n.s.
	Chiayi	20.4	19.7	0.7 **
Average	Taipei	25.2	25.0	0.2 n.s.
	Chiayi	27.2	26.8	0.4 n.s.

Note 1: The analysis period was 1:00 am − 5:00 am.
Note 2: *** refers to $p < 0.001$, ** refers to $p < 0.01$, and n.s. refers to no significant difference.

Table 8
The *t*-test analysis of indoor thermal effectiveness at nighttime on the rainy days.

Temperature (°C)		Reference point	Module	Temperature difference
Spring	Taipei	22.5	22.7	−0.2 n.s.
	Chiayi	26.4	25.4	1.0 n.s.
Summer	Taipei	30.9	30.9	0.0 n.s.
	Chiayi	31.1	30.4	0.7 n.s.
Autumn	Taipei	25.8	25.6	0.2 n.s.
	Chiayi	27.7	27.7	0.0 n.s.
Winter	Taipei	17.5	18.3	−0.8 **
	Chiayi	19.1	18.2	0.9 *
Average	Taipei	24.6	24.8	−0.2 n.s.
	Chiayi	27.6	27.0	0.6 n.s.

Note 1: The analysis period was 1:00 am − 5:00 am.
Note 2: ** refers to $p < 0.01$, * refers to $p < 0.05$, and n.s. refers to no significant difference.

5. Conclusions and suggestions

5.1. Conclusions

5.1.1. The thermal effectiveness of an extensive green roof varies in different climates

Comparing the thermal effectiveness of extensive green roofs between Taipei and Chiayi, a significant difference in thermal effectiveness was found, confirming that the thermal effectiveness of an extensive green roof is closely related to the climate. The cooling effectiveness of the extensive green roof becomes more significant when the temperature of the environment is higher.

Based on the observations and measurements in this study, the maximum cooling effectiveness was up to 22.5 °C in the summer in Taipei and 25.1 °C in the summer in Chiayi, which are different from the results obtained by the observations in Singapore and India. This difference in the cooling effectiveness is the result of the different climates, green roof styles, building materials, etc. However, in terms of cooling effectiveness, it was re-verified that the green roof does have a significant cooling effectiveness in a variety of different regions.

5.1.2. The thermal effectiveness of an extensive green roof varies at different times of day

Considering the role of an extensive green roof in a heat transfer interface, it can be regarded as a passive temperature regulator. During the day, it can reduce the increase of the outdoor temperature by approximately 42% (Table 1) and the increase of the indoor temperature by 8% (Table 5). During the night, it can maintain 17% of the temperature in the outdoor environment, stabilizing the temperature change (Table 3).

The cooling effectiveness in the outdoor environment was the highest at noontime, which corresponds to the highest surface warming period [35]. The cooling effectiveness of the indoor environment was the highest in the afternoon, which is when the indoor slab reaches its highest temperature. The comparison of the outdoor and indoor observations showed that, with the insulation effectiveness, the floor slab postponed the indoor temperature increase. Together with an extensive green roof, the indoor temperature increased more slowly, indicating that the extensive green roof changed the heat conduction behavior of the roof, resulting in increased cooling effectiveness.

5.1.3. Rainfall will affect the thermal effectiveness of an extensive green roof

On the rainy days, the outdoor cooling effectiveness of an extensive green roof decreased from 42% to 28% (Tables 1 and 2) and the indoor cooling effectiveness decreased from 8% to 4%

(Tables 5 and 6). However, the extensive green roof continues to have a significant cooling effect.

Regarding the outdoor insulation effectiveness at nighttime, outdoor insulation effectiveness of the extensive green roof was reduced from 17% to 13% on the rainy days (Tables 3 and 4). With respect to the change in the indoor temperature at nighttime, with the double influences of the roof slab and water level in stabilizing the temperature, the indoor thermal effectiveness of the extensive green roof decreased during the rainy days and exhibited different behaviors during different seasons.

5.2. Suggestions

In this study, the experimental observations in the actual atmospheric environment were made based on the roofs of the buildings in two university campuses located in northern and central southern locations Taiwan. The research results focused on the impact of the climatic conditions on the thermal effectiveness of an extensive green roof. The research observations showed the additive temperature regulating effect of the floor slab and the green roof. As Sailor [10] suggested, the green roof can be considered to be the outermost layer of a building. The installation of a green roof changes the heat transfer behavior of the roof slab. Considering this additive effect, the relationship of the additive effect can be explored in greater depth in the future in terms of the heat transfer characteristics of the building floor slab and the characteristics of the extensive green roof, including the thickness of the substrate, the substrate formulation, the moisture, the plant species, the configuration, and the structure. This information would further contribute to the development of the passive climate regulation of green roofs and the enhancement of the additive effects.

Additionally, many studies have raised the importance of the regional validation. This study mainly investigated the thermal effectiveness under the tropical and sub-tropical island climates. The research results are provided as a reference to promote the extensive green roof as a cooling method in Taiwan. The impact of more climate backgrounds on the thermal effectiveness can be further explored in the future, like surrounding wind speed and solar radiation. In addition, the rainfall influences, including rainfall duration, rainfall intensity, and water accumulation on the roof and in the extensive green roof components can be further investigated. Cooperating with the building structure and configuration, a more specific construction proposal could be provided for different climatic conditions, with an additive effect with the floor slab and the green roof.

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