Energy and Buildings 129 (2016) 174–185

Contents lists available at ScienceDirect

Energy and Buildings

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

Reduction of temperatures and temperature fluctuations by hydroponic green roofs in a subtropical urban climate

Yi-Yu Huang[a,b,c,*], Chien-Teh Chen[d], Yen-Chi Tsai[e]

[a] Department of Landscape Architecture, Tunghai University, B.S., Taiwan
[b] Department of Landscape Architecture, University of Pennsylvania M.L.A., United States
[c] Department of City and Regional Planning, Cornell University, Ph.D., United States
[d] National Chung Hsing University, Department of Agronomy, College of Agriculture & Natural Resources, Taiwan
[e] Tunghai University, Department of Landscape Architecture, Taiwan

ARTICLE INFO

Article history:
Received 11 February 2016
Received in revised form 20 June 2016
Accepted 10 July 2016
Available online 16 July 2016

Keywords:
Hydroponic green roof
Thermal performance
Heat amplitude
Subtropical climate

ABSTRACT

The heat island effect has resulted in higher urban temperatures. Green roofs could contribute to cooling, providing insulation to buildings, and lead to substantial savings in energy for temperature control. This study compared the effects of hydroponic green roofs on the reductions of rooftop temperature and heat amplitude. Treatments include water depths, plant types and growth mediums. The experimental site was located in Taichung, the third largest city of Taiwan, which has a subtropical climate. The results indicate that, first, a water depth of 10 cm is sufficient to provide an ideal hydroponic green roof system that reduced rooftop temperatures and heat amplitude by 5 °C and 55%, respectively. Second, when vegetation was added to the ideal hydroponic roof, the rooftop temperature was further reduced by 3 °C to 5 °C and the rooftop heat amplitude was further reduced by 16%, compared with the corresponding values for the roof without vegetation. However, between the two types of plants tested, no differences were observed in the reduction of rooftop temperature and heat amplitude. Third, the solid-type growth medium slightly outperformed the hydroponic-type growth medium in reducing the rooftop temperature; however, the solid-type was more challenging regarding system installation, maintenance, and weed control.

1. Introduction

Cities worldwide are constantly expanding at the expense of green spaces. The "heat island effect," caused by building structures and impermeable pavement retaining more heat than natural surfaces do, has resulted in higher urban temperatures compared with those of surrounding rural areas. Urban landscape modifications have resulted in a decrease in canopy interception and plant evapotranspiration has further intensified the heat island effect. With the projected increase in global temperatures, scientists generally agree that the global hydrological cycle will intensify, which could increase the frequency of extreme weather [1,2]. Therefore, a green roof system that could cool the city merits investigation.

Researchers have confirmed that green roofs contribute to cooling and providing insulation to buildings [3,4], which could lead to significant savings in energy used for air conditioning in summer and heating in winter [5–7]. The increase in greenery can further help mitigate the heat island effect and increase environmental comfort [8–10]. In addition, green roofs have other benefits such as stormwater management [2,11], air quality improvements [12], habitat creation [13], noise reduction [14], and the provision of recreational space in crowded cities. Green roof systems have made great advances in studies on plant species and plant substrate selections [15–17], irrigation experiments [16], flood and drought tolerance analyses of vegetation [18], and domestic wastewater treatment [19]. Recently, the terrestrial green roof system, particularly extensive green roof systems, and species of drought-adapted succulents (genus *Sedum*) have become favorites for populating green roofs [20,21]. However, the potential use of hydroponic systems for green roofs has been largely overlooked.

Two main types of green roof are discussed in this study. On extensive green roofs, plants are planted in a solid-type growth medium (e.g., peaty soil, perlite, vermiculite, or sandyloam soil). On hydroponic green roofs, plants are planted on top of precasted plastic planters floating on a water substrate.

* Corresponding author at: Department of Landscape Architecture, Tunghai University, Taiwan.
E-mail addresses: yyhuang@thu.edu.tw (Y.-Y. Huang), ctchen41@nchu.dragon.edu.tw (C.-T. Chen), delay36@yahoo.com.tw (Y.-C. Tsai).

http://dx.doi.org/10.1016/j.enbuild.2016.07.023
0378-7788/

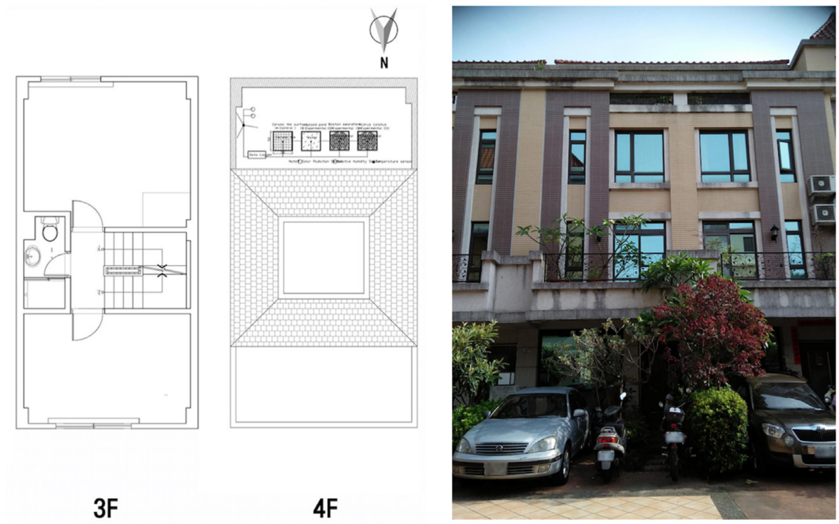

Fig. 1. Floor plans of the third floor (left) and the fourth floor (middle). Four blocks on the fourth floor are four experiment blocks (middle). Building facade for two residential units (right).

Alexandri and Jones, who studied the heat island effect in Athens (subtropical Mediterranean climate, hot and dry) argued that, compared with extensive green roofs, pond roofs without a plant layer can contribute to higher rooftop temperature reduction during the daytime [22]. Song et al. demonstrated that a wetland roof could reduce the rooftop temperature by an average of 4.9 °C in South Korea in August [18]. Moreover, Alexandri and Jones demonstrated that the rooftop temperature of a pond roof was significantly higher than that of an extensive green roof owing to the high heat capacity of water during nighttime. Thus, we investigated the following objectives in a subtropical climate not only in daytime but also in nighttime.

The following research objectives were investigated during the hottest months in Taiwan:

1 To investigate the thermal performance of hydroponic roofs with different depths of water substrates;
2 To investigate the thermal performance of hydroponic roofs with and without vegetation;
3 To compare the thermal performance of hydroponic green roofs and extensive green roofs.

2. Materials and methods

2.1. Research site

Field measurements were carried out on the rooftop of a three-story building (24°05′55.31″ N, 120°41′21.49″ E) in the Taichung metropolitan area, the third biggest city in Taiwan. The building is located in a subtropical monsoon climate. The building is a typical townhouse with two partial, flat concrete slab rooftops covered with ceramic tiles at the front and back of the building. Typically, two rooms are located directly underneath the two flat concrete slab rooftops—one in the front and the other in the back. In a building such as this, the installation of a green roof system on the flat concrete slab rooftop should reduce the temperature of the rooms on the third floor (Fig. 1). The experiment months, July, August, and September, were the three hottest months in Taiwan in 2014.

2.2. Plant types

Two species were investigated in this study: *Nephrolepis exaltata* (the Boston sword fern) and *Acorus calamus* (the sweet flag) (Fig. 2). *Nephrolepis exaltata* has layered, alternating pinnae that are 25–30 cm long and 7–9 cm broad. *Acorus calamus* has upright, dense, and slender leaves. These two species were investigated because they can both thrive well in a wide spectrum of

Fig. 2. *Nephrolepis exaltata* (left) and *Acorus calamus* (right).

Fig. 3. Glass tanks containing plants placed on top of cement boards.

environmental conditions. They could grow well in either a hydroponic or extensive green roof system. These species are also commonly found in gardens. Both are perennial species, which can reduce the costs of replanting.

2.3. Experimental design

In early July 2014, four 50 × 50 × 10-cm (L × W × H) cement boards capped with ceramic tiles were placed on a flat rooftop to simulate a bare roof (Fig. 3). Four 50 × 50 × 4-cm (L × W × H) Styrofoam boards were placed under the cement boards to block heat conduction from the surrounding bare roof. All cement boards were exposed to ample sunlight with potential interference of shadows from the parapets and sidewall of the fourth-floor room before 08:30 and after 15:30. These shadows were expected to grow shorter during July, August, and September. Three 50 × 50 × 30-cm (L × W × H) glass tanks were placed on top of three cement boards, and one cement board was exposed directly to the sunlight to simulate a bare roof as a control (Fig. 3). These experiment tanks were approximately the same size used in the studies of Fang [23] and Song et al. [18]. Typically, a bedroom or study room is located directly under a flat rooftop. Thus, a hydroponic green roof on a flat rooftop should help reduce the temperature of the rooms below.

The experiment consisted of three stages. The first stage involved comparing the thermal performance of a hydroponic roof with three depths of water: 10 cm, 20 cm, and 30 cm (Fig. 4). The second stage entailed comparing the thermal performance of a hydroponic roof with and without vegetation (Fig. 5). A water depth of 10 cm without any vegetation was compared with a water depth of 10 cm with floating planters of *Nephrolepis exaltata*, as well as a water depth of 10 cm with floating planters of *Acorus calamus*. According to pretest experiments, the thermal effect of floating planters was negligible. The third stage involved comparing the thermal performance of a hydroponic roof with *Acorus calamus* with that of an extensive green roof with the same type of plant (Fig. 6). *Acorus calamus* was used instead of *Nephrolepis exaltata* because it demonstrates greater heat dissipating ability during the evening, which could help reduce cooling energy loads during evening. Floating planters of *Acorus calamus* in a water depth of 10 cm were compared with the same type of plant in a solid medium with a depth of 10 cm (Fig. 6). The solid medium was a mixture of peaty soil, vermiculite, perlite, and sandy loam soil at a ratio of 1:1:1:1 [23].

2.4. Equipment description and parameter

Measuring points were positioned at the bottom center of each glass tank and at the center of the simulated bare roof. Thermocouples (12-Bit Temperature Smart Sensor, S-TMP-M002, Onset Computer Corporation) were placed in close contact with the surface to measure the temperature accurately. Air temperature, relative humidity, and solar radiation data were collected at a height of 150 cm above the rooftop surface and 125 cm from the nearest sidewall of the fourth-floor room to eliminate as much reflected solar radiation as possible from the rooftop surface and nearest sidewall, respectively [4,16] (Fig. 7) [18]. Three weather data loggers (HOBO Micro Station Data Logger, Onset Computer Corporation) with four channels were employed to collect all measurements. An interval of 10 min between measurements was specified. The experiment period for the first stage ran from 2014/07/27 to 2014/8/05, the second stage ran from 2014/08/13 to 2014/08/22, and the third stage ran from 2014/09/06 to 2014/09/15.

The temperature reduction effect was measured by subtracting the temperature of the simulated bare roof (controls) by the temperature readings from the experiments. The heat amplitude reduction was calculated as one minus the result of dividing the experimental temperature fluctuations by the simulated rooftop (controls) temperature fluctuation.

3. Results and discussion

3.1. Temperature, relative humidity and solar radiation

The data for air temperature, rooftop temperature, solar radiation, and relative humidity are shown in Table 1. The daily air temperatures and solar radiation for the entire experiment period are shown in Fig. 8. The mean air temperatures for the first,

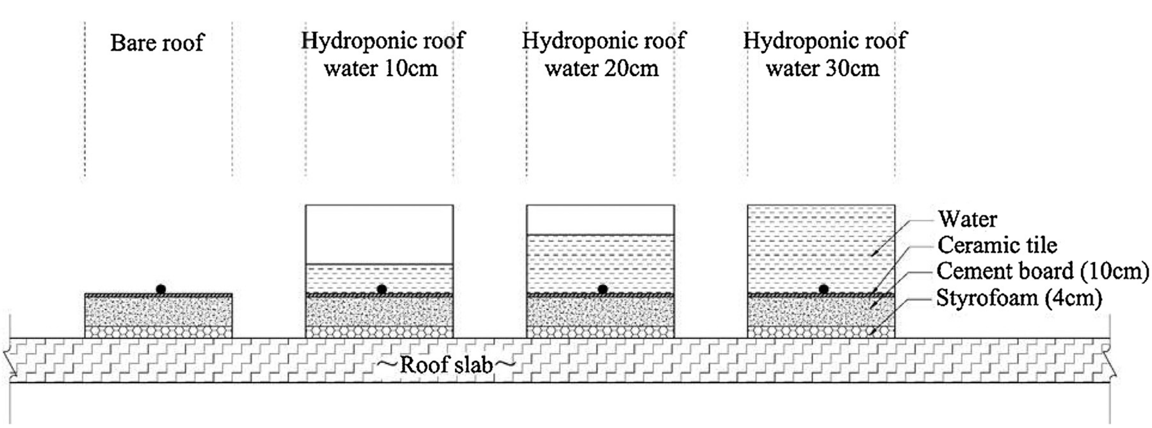

Fig. 4. Cross section of the first stage.

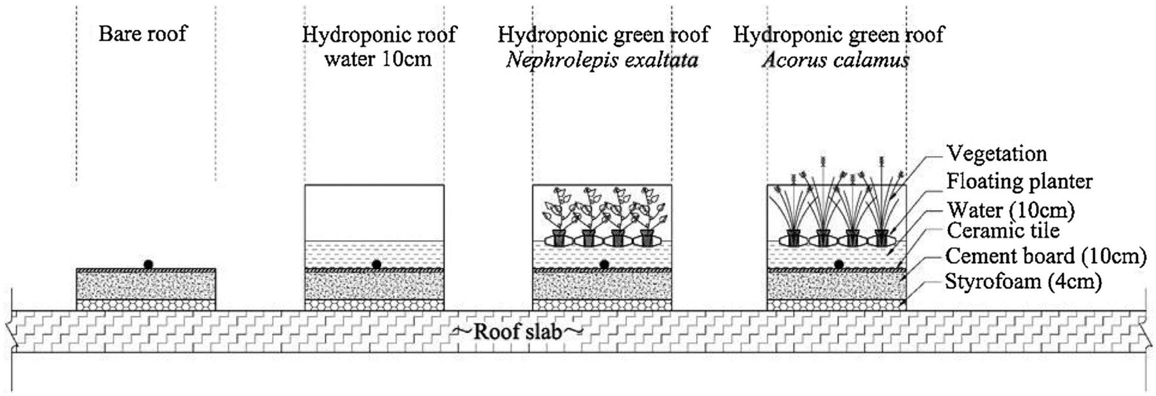

Fig. 5. Cross section of the second stage.

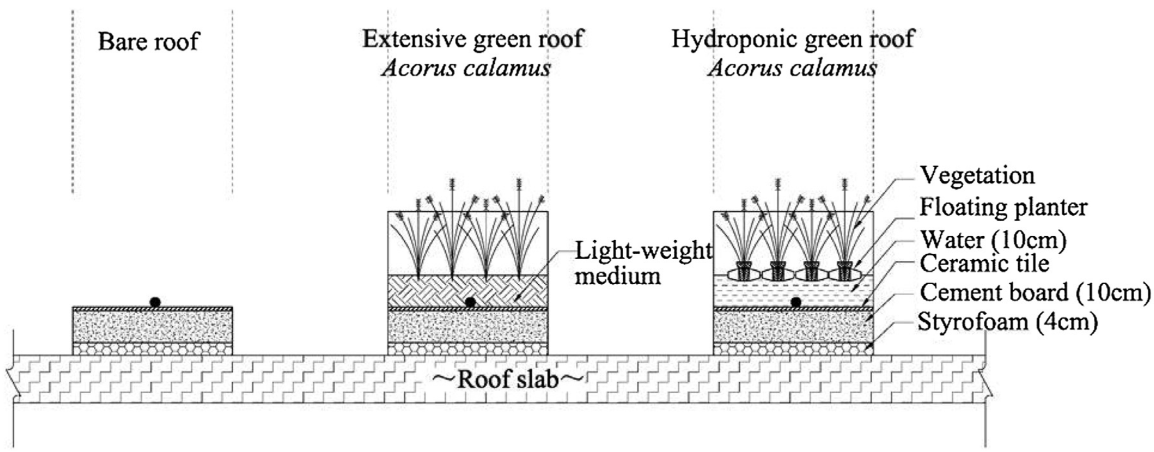

Fig. 6. Cross section of the third stage.

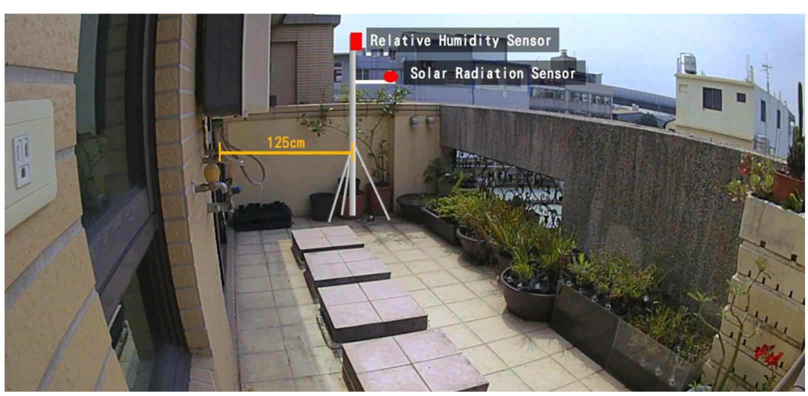

Fig. 7. Air temperature, relative humidity, and solar radiation measurements were performed at a height of at least 150 cm above the rooftop surface and 125 cm from the nearest sidewall.

Table 1
Weather data for the experiment site in Taichung, Taiwan (2014/07/27 06:00–2014/09/16 06:00).

Stage Parameter	First stage	Second stage	Third stage
Period of measurement	2014/07/27–08/05	2014/08/13–08/22	2014/09/07–09/16
Range of air temperature (°C)	25.94–37.02	23.91–37.29	26.40–38.81
Mean air temperature	30.99	29.92	31.61
Range of rooftop temperature (°C)	26.45–51.92	26.30–57.06	28.59–57.70
Mean rooftop temperature	34.54	33.73	37.36
Maximum solar radiation (W/m^2)	931.9	861.9	868.1
Mean relative humidity (%)	75.26	74.86	69.74
Date picked for further analysis	2014/08/04–05	2014/08/21–22	2014/09/15–16

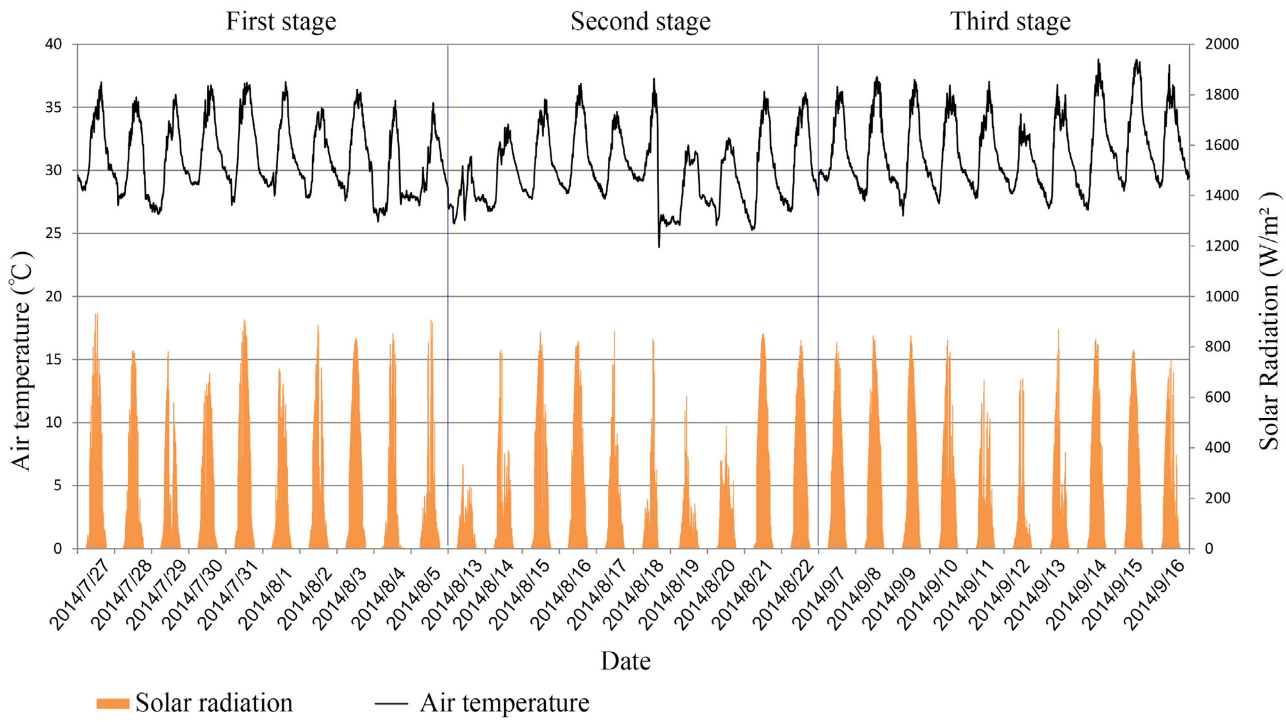

Fig. 8. Air temperature and solar radiation measurements (2014/07/27 06:00–2014/09/16 06:00).

second, and third stages were 30.99, 29.92, and 31.61 °C, respectively, and the mean rooftop temperatures were 34.54, 33.73, 37.36 °C, respectively. The mean relative humidity for the three stages were 75.26%, 74.86%, and 69.74%. The air temperature range was 25.94–37.02 °C for the first stage, 23.91–37.29 °C for the second stage, and 26.40–38.81 °C for the third stage. The rooftop temperature range was 26.45–51.92 °C for the first stage, 26.30–57.06 °C for the second stage, and 28.59–57.70 °C for the third stage.

For each stage, one full day from 06:00 to 06:00 of the next day was investigated for analyses. The reason for selecting 06:00 as the start of data analyzed and end at 06:00 the next day is because sun rose around 05:30 during July to September in 2014 [24], and the rooftop temperature started to rise after sun rose. The selection criteria for three days analyzed were a high temperature at noon, a stable air temperature progression during the whole day, as well as ample solar radiation with as little interference from clouds as possible. According to these criteria, the following days represent the first, second, and third stages, respectively: August 4, 06:00 to August 5, 06:00 (Fig. 9); August 21, 06:00 to August 22, 06:00 (Fig. 10); and September 15, 06:00 to September 16, 06:00 (Fig. 11). For these days, the reductions in temperature and in heat amplitude were calculated.

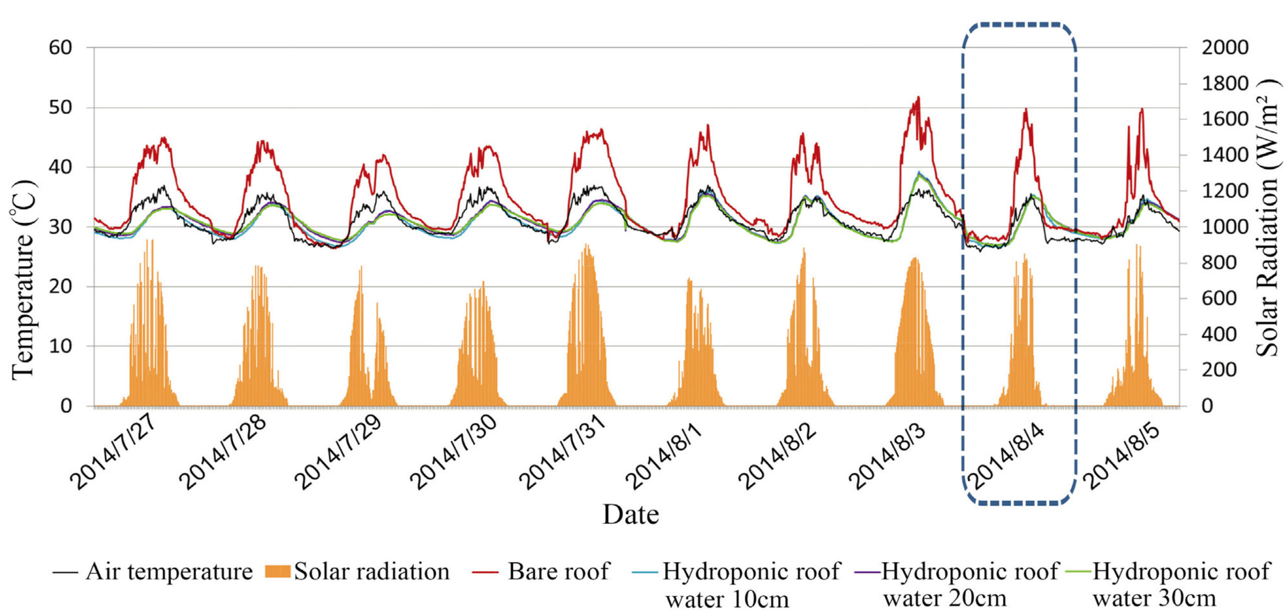

Fig. 9. Air temperature and temperatures for the hydroponic roof at different water depths (2014/07/27 00:00–2014/08/05 24:00).

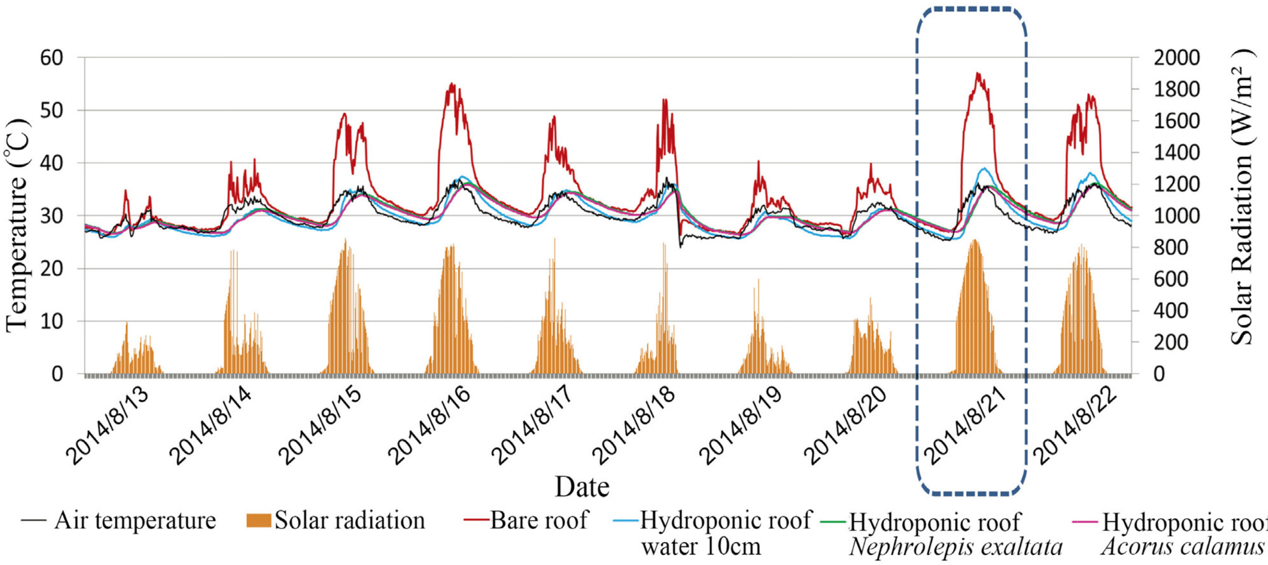

Fig. 10. Air temperature and temperatures for the hydroponic roof with and without vegetation (2014/08/13 00:00–2014/08/22 24:00).

3.2. Thermal performance of the hydroponic roof at different water depths

The first stage involved investigating whether a deeper water depth improved the performance of a hydroponic roof in reducing rooftop temperatures. On August 4, when the average air temperature was 30.72 °C, the average rooftop temperature was 36.10 °C and the average bottom temperatures of the hydroponic roofs at 10, 20, and 30 cm depths of water were all around 31 °C (Table 3). On August 4 at 12:00–13:00, the hydroponic roofs with 10, 20, and 30 cm depths of water all contributed to reduce the rooftop temperature around 15 °C, respectively (Table 2, Figs. 12 and 13). Since water has high heat capacity [22] and is a slow transfer medium for the delay of heat intrusion [18], a hydroponic roof with water alone can effectively prevent excessive rooftop temperature increases in summer, thereby reducing rooftop temperatures by approximately 5 °C on average, and by a maximum of approximately 15 °C.

The first stage involved investigating whether a deeper water depth improved the performance of a hydroponic roof in reducing rooftop temperatures. On August 4, when the average air temperature was 30.72 °C, the average rooftop temperature was 36.10 °C and the average bottom temperatures of the hydroponic roofs at 10, 20, and 30 cm depths of water were all around 31 °C (Table 3). On August 4 at 12:00–13:00, the hydroponic roofs with 10, 20, and 30 cm depths of water all contributed to reduce the rooftop temperature around 15 °C (Table 2, Figs. 12 and 13). Since water has high heat capacity [22] and is a slow transfer medium for the delay of heat intrusion [18], a hydroponic roof with water alone can effectively prevent excessive rooftop temperature increases in summer, thereby reducing rooftop temperatures by approximately 5 °C on average, and by a maximum of approximately 15 °C. This result is similar to Wu's finding that no significant difference in rooftop temperature reduction was observed between pond roofs with depths of 10, 20, and 30 cm depths of water [25]. This could due to the transparent and self-circulating properties of water; its shielding and shading effects are relatively poor compared with those of solid medium.

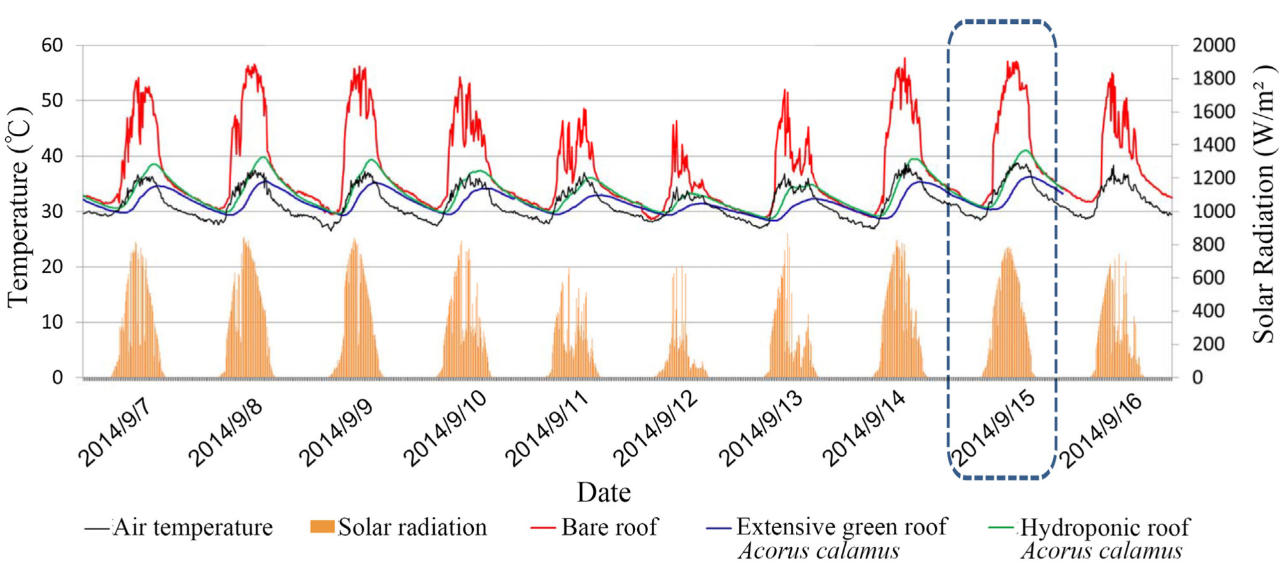

Fig. 11. Air temperature and temperatures for the hydroponic green roof and the extensive green roof (2014/09/07 00:00–2014/09/16 24:00).

Table 2
Bottom temperature and temperature reduction of hydroponic roofs at different water depths (2014/08/04 06:00–2014/08/04 18:00).

Thermocouple Position		06:00–07:00 (°C)	07:00–08:00 (°C)	08:00–09:00 (°C)	09:00–10:00 (°C)	10:00–11:00 (°C)	11:00–12:00 (°C)	12:00–13:00 (°C)	13:00–14:00 (°C)	14:00–15:00 (°C)	15:00–16:00 (°C)	16:00–17:00 (°C)	17:00–18:00 (°C)
Air temperature		26.63	26.93	27.32	29.83	31.80	32.68	34.03	34.75	34.09	32.69	30.19	27.67
Rooftop temperature		27.97	28.31	28.50	32.05	39.57	42.75	48.18	46.15	40.50	37.05	32.00	30.21
At the bottom	Water 10 cm	26.68	26.86	27.06	27.90	29.49	31.11	33.19	34.74	35.16	34.68	33.33	31.63
	Water 20 cm	27.06	27.15	27.27	27.94	29.48	31.08	32.94	34.48	35.01	34.61	33.82	32.45
	Water 30 cm	27.01	27.08	27.17	27.79	29.33	31.00	32.96	34.52	35.03	34.64	33.84	32.41
Temperature Reduction	Water 10 cm	1.29	1.46	1.44	4.15	10.09	11.64	14.99	11.42	5.34	2.37	−1.34	−1.42
	Water 20 cm	0.91	1.16	1.23	4.11	10.10	11.67	15.25	11.67	5.50	2.44	−1.82	−2.24
	Water 30 cm	0.96	1.24	1.33	4.26	10.24	11.75	15.22	11.64	5.48	2.41	−1.85	−2.20

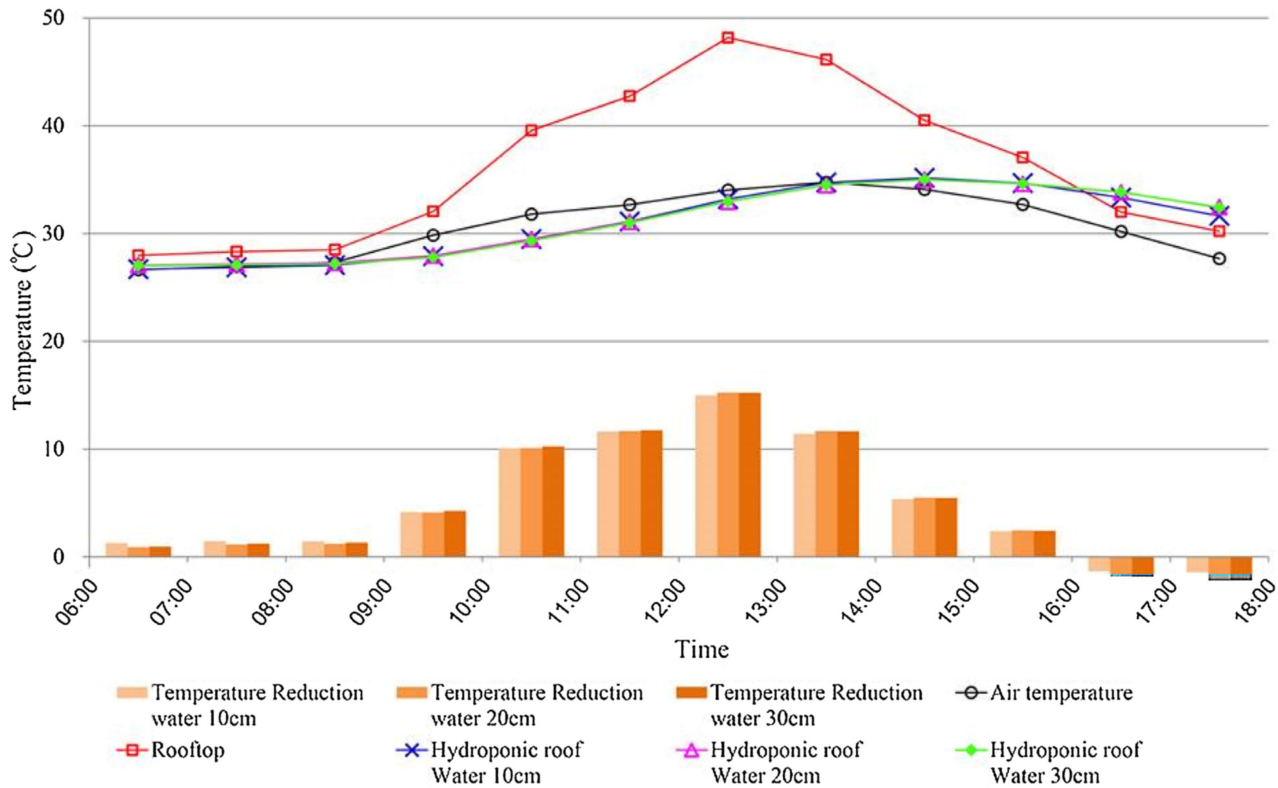

Fig. 12. Temperature and temperature reduction of hydroponic roofs at different water depths (2014/08/04 06:00–18:00).

In addition to reducing the rooftop temperature, the hydroponic roof also contributes to rooftop temperature stabilization. This helps mitigate the fluctuation of indoor temperatures [18] and thus increase the comfort level. On August 4 (06:00–18:00), the hydroponic roofs with water alone contributed to a heat amplitude reduction of 60.6%, 63.5%, and 63.5% for 10, 20, and 30 cm depths of water, respectively (Table 3). The heat amplitude reduction was calculated as one minus the result of dividing the experimental temperature fluctuations by the simulated rooftop (controls) temperature fluctuation. This result is similar to findings by Alexandri and Jones [22]. Since water has a high heat capacity, it helped absorb a substantial amount of solar radiation, which resulted in retarding the temperature increase of the rooftops [18].

In brief, hydroponic roofs with 10 cm depth of water or more have the potential to reduce rooftop temperatures by 5 °C on average and by 15 °C at the maximum, and to reduce the heat amplitude by more than 60%. Based on the weight load and safety of a building, a hydroponic roof with 10 cm depth of water works most efficiently because the marginal increase in rooftop temperature reduction is less than 0.3 °C exceeding 10 cm depth of water. Consequently, 10 cm depth of water substrate was used for the second and third stages.

Table 3
Heat amplitude reductions for hydroponic roofs at different water depths (2014/08/04 06:00–18:00).

Thermocouple Position		Average temperature (°C)	Range of temperature (°C)	Difference in temperature (°C)	Reduction percentage of heat amplitude
Air temperature		30.72	26.43 ~ 35.53	9.10	
Rooftop temperature		36.10	27.73 ~ 49.92	22.19	
At the bottom	Water 10 cm	30.98	26.65 ~ 35.40	8.75	60.57%
	Water 20 cm	31.11	27.04 ~ 35.13	8.09	63.54%
	Water 30 cm	31.06	26.99 ~ 35.10	8.11	63.45%

Note: The reduction percentage of heat amplitude is calculated by one minus the result of dividing the temperature fluctuation of experiments by the temperature fluctuation of the simulated bare rooftop.

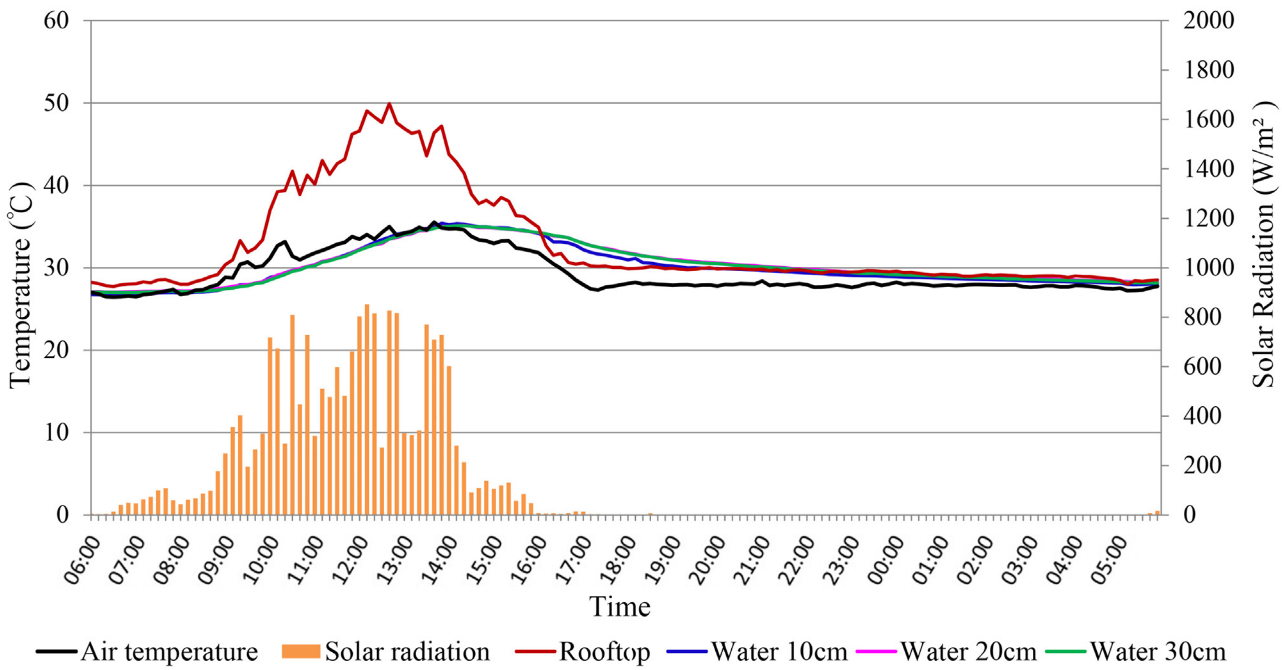

Fig. 13. Solar radiation and temperatures for hydroponic roofs at different water depths (2014/08/04 06:00–2014/08/05 06:00).

3.3. Thermal performance of the hydroponic roof with and without vegetation

The second stage entailed investigating the effect of hydroponic green roofs and hydroponic plants alone in reducing the rooftop temperature and heat amplitude. On August 21, when the average air temperature was 32.42 °C, the average rooftop temperature was 43.96 °C, the average bottom temperature of the hydroponic roof with 10 cm depth of water alone was 32.68 °C, the average bottom temperature of the hydroponic roof with 10 cm depth of water and *Nephrolepis exaltata* was 31.38 °C, and the average bottom temperature of the hydroponic roof with 10 cm depth of water and *Acorus calamus* was 31.42 °C (Table 5). In addition, on August 21 at 12:00–13:00, the hydroponic roof with vegetation reduced the rooftop temperature to 23.03–23.41 °C, which was 3–5 °C more than that of the hydroponic roof without vegetation (19.15 °C) (Table 4, Figs. 14 and 15). There was no significant difference in temperature reduction between *Nephrolepis exaltata* and *Acorus calamus*. Our hydroponic green roof contributed to a 12–13 °C reduction in rooftop temperature; this outperformed those of Song et al. [18], in which their wetland roof contributed to a reduction of 4.9 °C. This difference is mainly because Song et al.'s experiment was conducted in early May when the mean temperature was only 21.1 °C, whereas our experiment was conducted during the hottest month in Taiwan, when the mean air temperature reached as high as 32.4 °C. Consequently, regardless of the high relative humidity, which may hamper the cooling capabilities of hydroponic roofs [26], our results clearly demonstrate the great benefit of hydroponic green roofs in alleviating rooftop temperatures in a hot, humid, subtropical climate zone.

Our results demonstrated that the higher the air temperature is, the higher the rooftop temperature becomes; thus, the higher the potential of vegetation in reducing the rooftop temperature. In addition, vegetation provides shielding and shading effects to the rooftop, and, compared with water evaporation, evapotranspiration by plants releases more heat and results in a greater reduction in rooftop temperatures than does water alone [18]. Scientists generally agree that in the future, summers will become hotter and winters will become colder because of climate change; hydroponic vegetation can serve to greatly reduce rooftop temperature during summer and provide better insulation during winter. Consequently, a hydroponic green roof can contribute toward reducing the utility costs of households throughout the whole year.

Our results also clearly show that the hydroponic roof with vegetation contributed to a higher reduction in heat amplitude than did the roof without vegetation. On August 21 (06:00–18:00), the hydroponic roof with vegetation reduced the heat amplitude by 71.21%–71.51%, which was 15%–16% more than that of the hydroponic roof without vegetation (55.37%) (Table 5). The previous researchers tended to emphasize the thermal performance of the entire extensive green roof system [22], to the best of our knowledge, no researcher estimated the thermal performance of vegetation layer alone. Our results demonstrated that the thermal performance of a single vegetation layer is insufficient.

Table 4
Bottom temperatures and temperature reductions for hydroponic roofs with and without vegetation (2014/08/21 06:00–18:00).

Thermocouple Position		06:00–07:00 (°C)	07:00–08:00 (°C)	08:00–09:00 (°C)	09:00–10:00 (°C)	10:00–11:00 (°C)	11:00–12:00 (°C)	12:00–13:00 (°C)	13:00–14:00 (°C)	14:00–15:00 (°C)	15:00–16:00 (°C)	16:00–17:00 (°C)	17:00–18:00 (°C)
Air temperature		25.65	27.49	30.75	32.09	33.48	34.31	35.31	35.04	35.48	34.72	33.21	31.48
Rooftop temperature		27.13	27.79	28.84	45.09	50.13	52.94	55.95	55.25	53.88	50.00	43.58	37.01
At the bottom	Water 10 cm	25.69	25.63	25.89	27.36	30.80	34.15	36.79	38.52	38.76	37.77	36.18	34.60
	Nephrolepis exaltata	27.15	27.01	27.10	27.71	29.09	30.83	32.53	34.10	35.24	35.61	35.35	34.80
	Acorus calamus	27.04	26.95	27.18	28.06	29.63	31.37	32.91	34.27	35.26	35.40	34.86	34.13
Temperature Reduction	Water 10 cm	1.45	2.17	2.96	17.73	19.33	18.79	19.15	16.73	15.12	12.24	7.39	2.41
	Nephrolepis exaltata	−0.01	0.79	1.74	17.38	21.04	22.10	23.41	21.15	18.64	14.39	8.23	2.21
	Acorus calamus	0.09	0.84	1.66	17.03	20.50	21.57	23.03	20.98	18.62	14.60	8.71	2.88

Table 5
Heat amplitude reductions for hydroponic roofs with and without vegetation (2014/08/21 06:00–18:00).

Thermocouple Position		Average temperature (°C)	Range of temperature (°C)	Difference in temperature (°C)	Reduction percentage of heat amplitude
Air temperature		32.42	25.36–36.25	10.89	
Rooftop temperature		43.96	27.01–57.06	30.05	
At the bottom	Water 10 cm	32.68	25.60–39.01	13.41	55.37%
	Nephrolepis exaltata	31.38	26.99–35.64	8.65	71.21%
	Acorus calamus	31.42	26.94–35.50	8.56	71.51%

Note: The reduction percentage of heat amplitude is calculated by one minus the result of dividing the temperature fluctuation of experiments by the temperature fluctuation of the simulated bare rooftop.

There was no significant difference in the reduction of heat amplitude between *Nephrolepis exaltata* and *Acorus calamus*. Because of the albedo, absorption, evapotranspiration, shielding, and shading effects of leaves, the hydroponic green roof with vegetation contributed to a greater reduction in heat gain and thus outperformed the hydroponic roof without vegetation [4,26,27]. In brief, our results clearly demonstrated that the heat-intrusion delay properties of hydroponic green roofs modulate temperature changes and hence benefit the buildings in which they are used. Hydroponic roofs with vegetation achieved improved thermal performance in reducing rooftop temperatures and heat amplitudes compared with hydroponic roofs of the same water depth without vegetation.

3.4. Thermal performance of the hydroponic green roof and extensive green roof

The third stage involved investigating the difference in rooftop temperature reductions between the hydroponic green roof and the extensive green roof, both planted with *Acorus calamus*. The reason for using *Acorus calamus* was that its upright and slender leaves have a more favorable heat dissipating effect in the evening than that of *Nephrolepis exaltata* (with dense and intricate layer of leaves). Since a hydroponic or extensive green roof tends to delay the heat release of a building, plant species with superior heat dissipation capability would help reduce energy loads during the evenings.

On September 15, when the average air temperature was 35.21 °C, the average rooftop temperature was 46.30 °C, and the average bottom temperature of the hydroponic green roof and the extensive green roof was 36.15 and 33.01 °C, respectively (Table 7). In addition, on September 15 (06:00–18:00), the extensive green roof contributed to a reduction in heat amplitude of 77.40%, which was 16% greater than that of the hydroponic green roof (60.49%) (Table 7). The result shows that with the same depth of the substrate (10 cm depth of the water substrate or 10 cm of the lightweight medium), the extensive green roof contributed to greater reductions in rooftop temperatures and heat amplitudes (Table 6, Figs. 16 and 17).

Our results do not confirm the findings of Alexandri and Jones [22]. First, although the rooftop temperature of the pond roof was

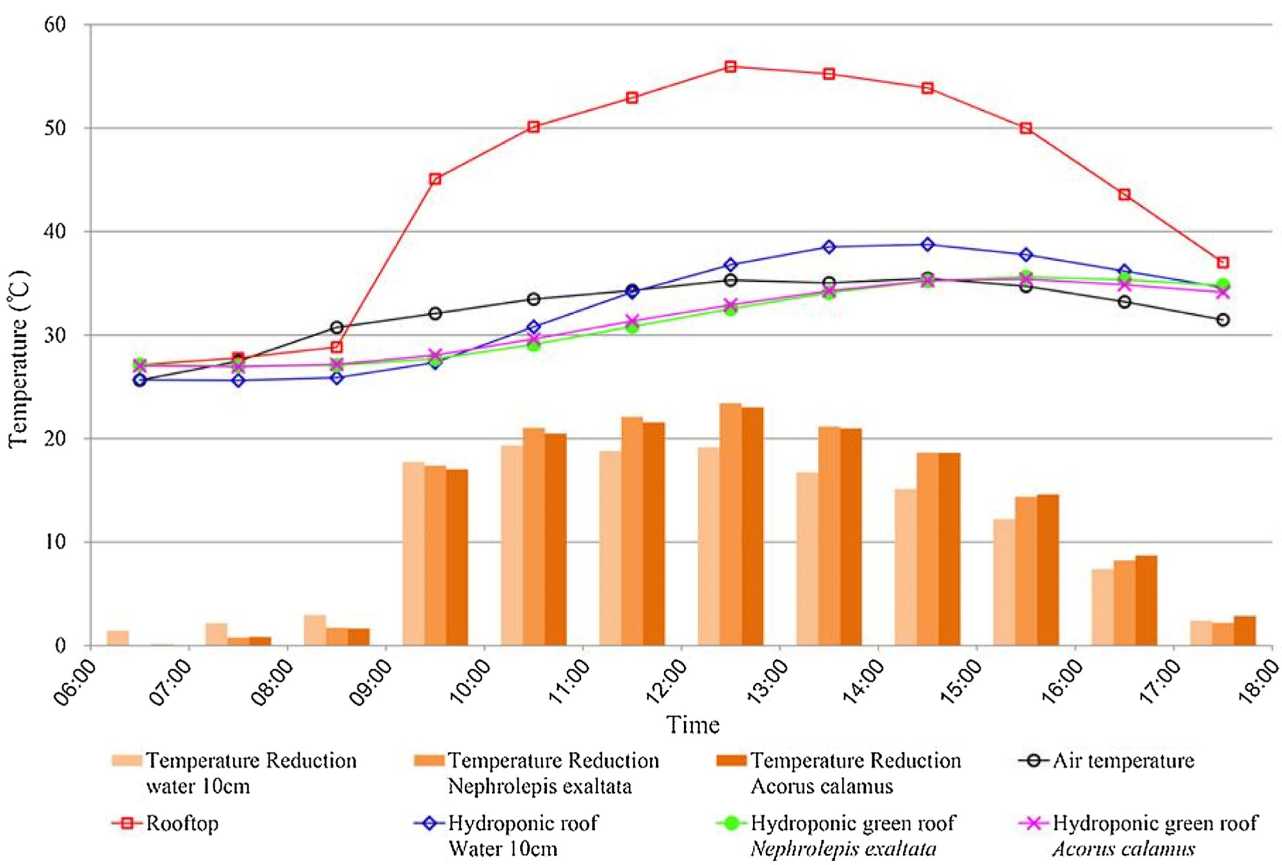

Fig. 14. Temperature and temperature reduction of hydroponic roofs with and without vegetation (2014/08/21 06:00 ~ 18:00).

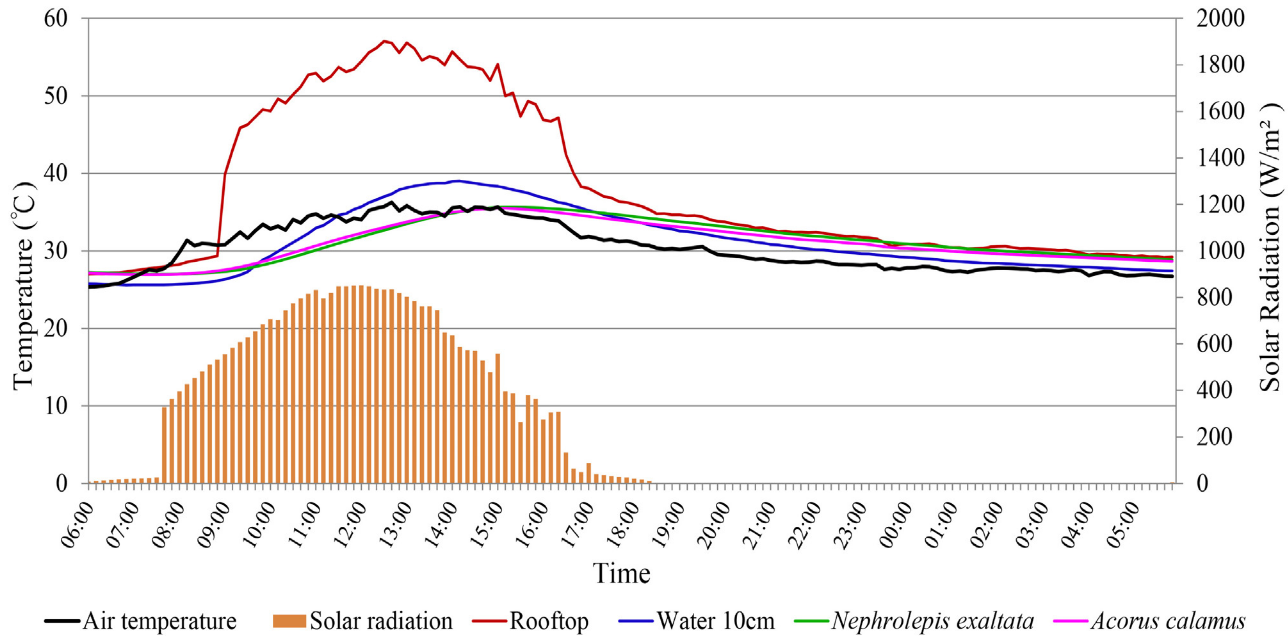

Fig. 15. Solar radiation and bottom temperatures for hydroponic roofs with and without vegetation (2014/08/21 06:00–2014/08/22 06:00).

Table 6
Bottom temperatures and temperature reductions for the hydroponic green roof and the extensive green roof (2014/09/15 06:00–18:00).

Thermocouple Position		06:00–07:00 (°C)	07:00–08:00 (°C)	08:00–09:00 (°C)	09:00–10:00 (°C)	10:00–11:00 (°C)	11:00–12:00 (°C)	12:00–13:00 (°C)	13:00–14:00 (°C)	14:00–15:00 (°C)	15:00–16:00 (°C)	16:00–17:00 (°C)	17:00–18:00 (°C)
Air temperature		28.96	30.81	32.84	33.48	35.14	36.58	37.68	38.47	38.1	38.12	37.4	34.96
Rooftop temperature		31.48	32.71	38.26	46.14	50.22	53.79	55.17	56.26	53.43	52.37	46.15	39.63
At the bottom	Extensive green roof	30.59	30.40	30.40	30.50	30.93	31.83	33.14	34.49	35.50	36.02	36.21	36.11
	Hydroponic green roof	30.83	30.77	31.17	32.31	34.09	36.04	37.71	39.22	40.47	40.98	40.67	39.51
Temperature Reduction	Extensive green roof	0.90	2.31	7.86	15.64	19.29	21.96	22.02	21.77	17.92	16.36	9.94	3.52
	Hydroponic green roof	0.65	1.94	7.09	13.83	16.13	17.76	17.46	17.04	12.96	11.39	5.48	0.12

significantly lower than that of the extensive green roof during the daytime in subtropical Mediterranean climate (Athens), the rooftop temperature of the hydroponic roof was higher than that of the extensive green roof during the daytime in subtropical climate (Taichung). In other words, the hydroponic green roof did not outperform the extensive green roof during the daytime in subtropical climate. This finding may be because the weather in July in Athens is hot and dry (relative humidity approximately 50%), and the weather in September in Taichung is hot and wet (relative humidity approximately 80%). The improved evaporation rate of water on the pond roof in Athens would help reduce the excessive heat of a rooftop surface.

Second, although the rooftop temperature of the pond roof was significantly higher than that of the extensive green roof during the nighttime in subtropical Mediterranean climate (Athens), the rooftop temperature of the hydroponic green roof and the extensive green roof tended to converge to the ambience temperature during the nighttime in subtropical climate (Taichung). This finding may be because Taiwan is the island country and thus has a more stable temperature compared to Athens. Consequently, the users of hydroponic green roofs do not need to be concerned that the hydroponic green roof may increase the energy load of a building during the evening in a subtropical climate (Taichung).

Nevertheless, the hydroponic green roof outperformed the extensive green roof in many other ways. First, the hydroponic green roof system demonstrated considerably higher capacity in flood control compared with that of the extensive green roof system. Due to different plant characteristics, a hydroponic green roof can hold significantly more stormwater runoff simply by increasing the maximum water depth in the system design; however, this should not exceed the load-bearing capacity of the building, or the load-bearing capacity should be increased to handle the excessive rainfall. Moreover, the height of the edge of an extensive green roof should not be increased markedly because terrestrial plants, which

Table 7
Reduction in heat amplitude for the hydroponic green roof and the extensive green roof (2014/09/15 06:00–18:00).

Thermocouple Position		Average temperature (°C)	Range of temperature (°C)	Difference in temperature (°C)	Reduction percentage of heat amplitude
Air temperature		35.21	28.69–38.78	10.09	
Rooftop temperature		46.30	31.08–57.10	26.02	
At the bottom	Extensive green roof	33.01	30.36–36.24	5.88	77.40%
	Hydroponic green roof	36.15	30.74–41.02	10.28	60.49%

Note: The reduction percentage of heat amplitude is calculated by one minus the result of dividing the temperature fluctuation of experiments by the temperature fluctuation of the simulated bare rooftop.

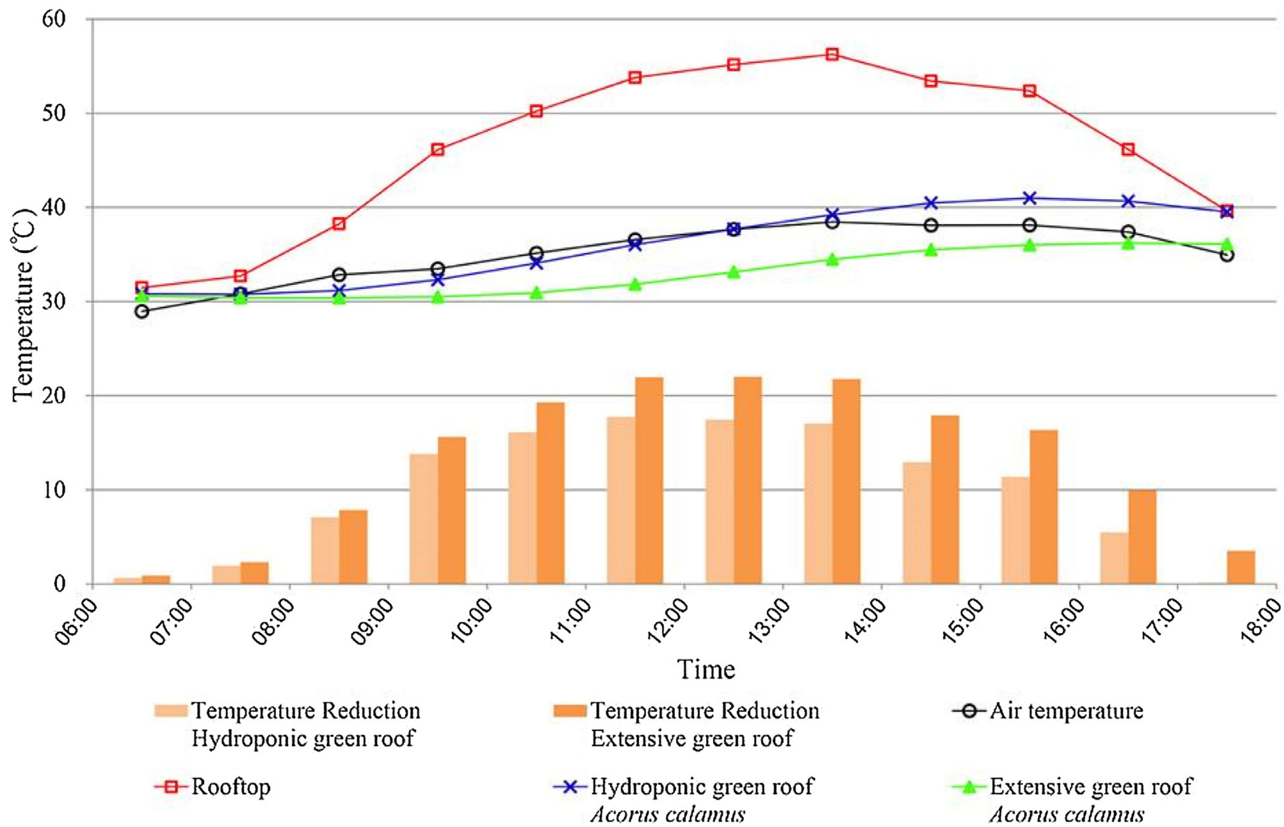

Fig. 16. Temperatures and temperature reductions for the hydroponic green roof and the extensive green roof (2014/09/15 06:00–18:00).

usually have a low tolerance to flooding, may drown after heavy rainfall or storms. In addition, with the same amount of irrigation, aqueous plants can grow well but terrestrial plants may be unable to survive [18].

Second, due to aqueous plant characteristics (collecting rainwater from time to time) and the increased water-holding capacity of aqueous plants [18], the irrigation need can be significantly reduced by a hydroponic green roof system. This contributes to considerable savings on precious water resources and utility costs.

Third, it is easier and more cost-effective to maintain a hydroponic green roof system than an extensive green roof system. The same plant can grow more favorably in 10 cm depth of water than in 10 cm depth of a light-weight medium, which may frequently undergo drought because of the harsh conditions on a rooftop. Furthermore, the problems of weed control, soil fertility loss, and root damage to the floor of the rooftop seldom arise in a hydroponic green roof system [28].

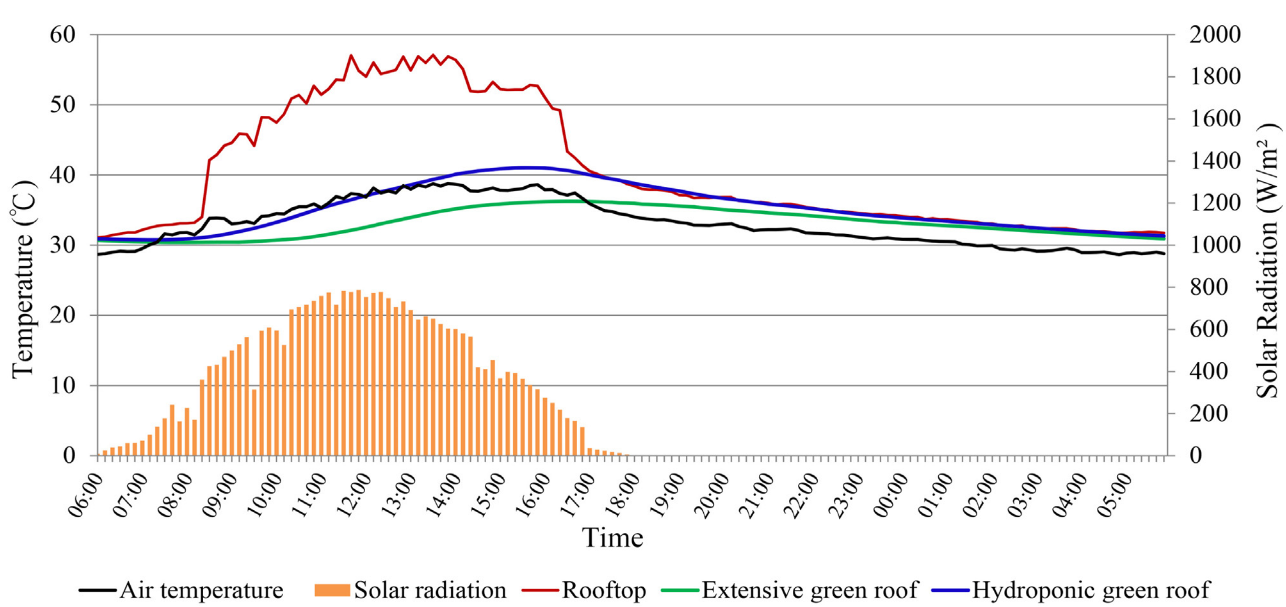

Fig. 17. Solar radiation and bottom temperatures for the hydroponic green roof and the extensive green roof (2014/09/15 06:00–2014/09/16 06:00).

4. Conclusions

Climate change will increase the odds of high ambient temperatures. Transforming numerous rooftops with unused space into green roofs is a cost-effective means of mitigating the heat island effect. In this paper, we conclude that a hydroponic roof with various water depths, and with or without plants can significantly mitigate the high rooftop temperature. Our main conclusions are as follows:

1 Due to the evaporation and insulation of water, a hydroponic roof with a water depth of 10 cm reduced the rooftop temperature by an average of 11 °C and a maximum of 19 °C, and reduced the heat amplitude by 60%. Although a water depth greater than 10 cm may result in a greater reduction in rooftop temperatures and heat amplitudes, the difference is insignificant. Consequently, to mitigate the weight load of building rooftops, our results demonstrate that a hydroponic roof with 10 cm depth of water is most cost-effective and sufficient to support a hydroponic green roof system.
2 Due to albedo, evapotranspiration, shielding, absorption, and shading effects of plants, a hydroponic green roof with 10 cm depth of water and *Nephrolepis exaltata* or *Acorus calamus* could reduce the rooftop temperature by an average of 12 °C and a maximum of 23 °C, and reduced the heat amplitude by 70%. However, the effect of vegetation is not as significant as expected. Nevertheless, vegetation is still strongly recommended for their visually pleasing, therapeutic, recreational, water purification, and biodiversity-increasing effects.
3 Comparing the hydroponic green roof planted with *Acorus calamus* with the extensive green roof planted with the same plant, the extensive green roof contributed to a greater rooftop temperature reduction and heat amplitude reductions because of convection and conducting effects as well as the transparent property of water substrates.

Overall, the hydroponic green roof is effective in reducing the rooftop surface temperature and in bringing comfort to the building. Although the extensive green roof slightly outperforms the hydroponic green roof in rooftop temperature reduction and the reduction in heat amplitude, the hydroponic green roof outperformed the extensive green roof in many other ways: excellent stormwater storage capability, lower irrigation needs, easy installation and removal of the system, low maintenance, superior weed control, more ecological services, no need to change the substrate after fertilizer deprivation, and no root damage to the concrete slabs of rooftops.

References

[1] H. Hisdal, K. Stahl, L.M. Tallaksen, S. Demuth, Have streamflow droughts in Europe become more severe or frequent? Int. J. Climatol. 21 (3) (2001) 317–333, http://dx.doi.org/10.1002/joc.619.
[2] J.C. Berndtsson, Green roof performance towards management of runoff water quantity and quality: a review, Ecolo. Eng. 36 (4) (2010) 351–360, http://dx.doi.org/10.1016/S0378-7788(02)00108-1.
[3] N.H. Wong, D.K.W. Cheong, H. Yan, J. Soh, C.L. Ong, A. Sia, The effects of rooftop garden on energy consumption of a commercial building in Singapore, Energy Build. 35 (4) (2003) 353–364, http://dx.doi.org/10.1016/j.buildenv.2005.07.030.
[4] W.N. Hien, T.P. Yok, C. Yu, Study of thermal performance of extensive rooftop greenery systems in the tropical climate, Build. Environ. 42 (1) (2007) 25–54, http://dx.doi.org/10.1016/j.buildenv.2005.07.030.
[5] I. Jaffal, S.E. Ouldboukhitine, R. Belarbi, A comprehensive study of the impact of green roofs on building energy performance, Renew. Energy 43 (2012) 157–164, http://dx.doi.org/10.1016/j.renene.2011.12.004.
[6] H.F. Castleton, V. Stovin, S.B.N. Beck, J.B. Davison, Green roofs; building energy savings and the potential for retrofit, Energy Build. 42 (10) (2010) 1582–1591, http://dx.doi.org/10.1016/j.enbuild.2010.05.004.
[7] C.Y. Jim, L.L.H. Peng, Weather effect on thermal and energy performance of an extensive tropical green roof, Urban For. Urban Greening 11 (1) (2012) 73–85, http://dx.doi.org/10.1016/j.ufug.2011.10.001.
[8] N.H. Wong, C. Yu, Study of green areas and urban heat island in a tropical city, Habitat Int. 29 (3) (2005) 547–558, http://dx.doi.org/10.1016/j.habitatint.2004.04.008.
[9] S.E. Gill, J.F. Handley, A.R. Ennos, S. Pauleit, Adapting cities for climate change: the role of green infrastructure, Built Environ. 33 (1) (2007) 115–133, http://dx.doi.org/10.2148/benv.33.1.115.
[10] M. Kohler, M. Schmidt, M. Laar, Green roofs as a contribution to reduce urban heat islands, World Clim. Energy Event 3 (2003) 493–498.
[11] B.G. Gregoire, J.C. Clausen, Effect of a modular extensive green roof on stormwater runoff and water quality, Ecol. Eng. 37 (6) (2011) 963–969, http://dx.doi.org/10.1016/j.ecoleng.2011.02.004.
[12] D.B. Rowe, Green roofs as a means of pollution abatement, Environ. Pollut. 159 (8-9) (2011) 2100–2110, http://dx.doi.org/10.1016/j.envpol.2010.10.029.
[13] R. Fernandez-Canero, P. Gonzalez-Redondo, Green roofs as a habitat for birds: a review, J. Anim. Vet. Adv. 9 (15) (2010) 2041–2052, http://dx.doi.org/10.3923/javaa.2010.2041.2052.
[14] T.V. Renterghem, D. Botteldooren, In-Situ measurements of sound propagating over extensive green roofs, Build. Environ. 46 (3) (2011) 729–738, http://dx.doi.org/10.1016/j.buildenv.2010.10.006.
[15] J.S. MacIvor, M.A. Ranalli, J.T. Lundholm, Performance of dryland and wetland plant species on extensive green roofs, Ann. Bot. 107 (4) (2011) 671–679, http://dx.doi.org/10.1093/aob/mcr007.
[16] Y.J. Lin, H.T. Lin, Thermal performance of different planting substrates and irrigation frequencies in extensive tropical rooftop greeneries, Build. Environ. 46 (2) (2011) 345–355, http://dx.doi.org/10.1016/j.buildenv.2010.07.027.
[17] J.S. MacIvor, J. Lundholm, Inspect species composition and diversity on intensive green roofs and adjacent level-ground habitats, Urban Ecosyst. 14 (2) (2011) 225–241, http://dx.doi.org/10.1007/s11252-010-0149-0.
[18] U. Song, E. Kim, J.H. Bang, D.J. Son, B. Waldman, E.J. Lee, Wetlands are an effective green roof system, Build. Environ. 66 (2013) 141–147, http://dx.doi.org/10.1016/j.buildenv.2013.04.024.
[19] B.X. Thanh, V.T.D. Hien, N.P. Dan, P.T.H. Van, N.T. Tin, Performance of wetland roof treating domestic wastewater in the tropic urban area, J. Water Sustain. 2 (1) (2012) 79–86, http://dx.doi.org/10.11912/jws.2.1.79-86.
[20] A. Nagase, N. Dunnett, Drought tolerance in different vegetation types for extensive green roofs: effects of watering and diversity, Landscape Urban Plann. 97 (4) (2010) 318–327, http://dx.doi.org/10.1016/j.landurbplan.2010.07.005.
[21] C. Farrell, R.E. Mitchell, C. Szota, J.P. Rayner, N.S.G. Williams, Green roofs for hot and dry climates: interacting effects of plant water use, succulence and substrate, Ecol. Eng. 49 (2012) 270–276, http://dx.doi.org/10.1016/j.ecoleng.2012.08.036.
[22] E. Alexandri, P. Jones, Ponds. green roofs, pergolas and high albedo materials; Which cooling technique for urban spaces? in: PLEA 2006-the 23rd Conference on Passive and Low Energy Architecture Proceeding, Geneva, Switzerland, 2006.
[23] C.F. Fang, The study of the thermal reduction effect on ecology roof in Central Taiwan Journal of Landscape 17 (4) (2011) 45–62.
[24] Central Weather Bureau, Sun Rise and Sun Set Time, 2015 (Retrieved February 11, 2016, from http://cwb.gov.tw).
[25] S.C. Wu, S.P. Feng, F.H. Lin, A study of the effect of roof pond on the temperature regulation in winter time, J. Sci. Technol. Humanit. Transw. 15 (2012) 30–43.
[26] M. Santamouris, Cooling the cities: a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments, Sol. Energy 103 (2014) 682–703, http://dx.doi.org/10.1016/j.solener.2012.07.003.
[27] S. Parizotto, R. Lamberts, Investigating of green roof thermal performance in temperate climate: a case of an experimental building in Florianopolis city, Southern Brazil, Energy Build. 43 (7) (2011) 1712–1722, http://dx.doi.org/10.1016/j.enbuild.2011.03.014.
[28] X.T. Wang, S.H. Lv, M.C. Chen, S.H. Chen, S.M. Huang, Z.W. Huang, S.G. Tsai, Aquaponics, Sharp, Taipei, 2015.