공학석사 학위논문

옥상녹화의 구성요소가 증발 및 잠열 전달에 미치는 영향

Effects of green roof components on the evaporation and latent heat transfer

2020년 8월

서울대학교 대학원

건설환경공학부

MALWINA SUCHANECKA

Effects of green roof components on the evaporation and latent heat transfer

옥상녹화의 구성요소가 증발 및 잠열 전달에 미치는 영향

By

Malwina Suchanecka

Advisor: Professor Mooyoung Han

A dissertation submitted in partial fulfilment of the requirements for the degree of Master in Civil and Environmental Engineering

August, 2020

Department of Civil and Environmental Engineering

College of Engineering

Seoul National University

Abstract

Effects of green roof components on the evaporation and latent heat transfer

Malwina Suchanecka
Dept. of Civil and Environmental Engineering
College of Engineering
Seoul National University

Rapid urbanization and expansion of urban areas have resulted in a decrease in permeability of the ground and a rise in its surface temperature, leading to the occurrence of urban heat islands (UHI). In recent years, green roofs have attracted growing attention as a potential strategy for UHI mitigation. However, previous studies did not consider the effect of green roof's evaporation on the amount of sensible heat released into the atmosphere. This study aims to evaluate two green roof components: growing substrate and water retention structure, in terms of its effect on green roof evaporation and latent heat transfer; and to propose the green roof design recommendations toward sensible heat flux reduction.

Plots of green roof growing substrate treated with two different soil amendments (superabsorbent polymer and rice husk biochar), as well as three water retention structures (granular layer, retention mat and retention plate),

along with one plot that combined both soil amendment and retention structure were examined in a specially designed evaporation reactor over a five-day period. Substrate surface temperatures, daily and cumulative evaporation, latent and sensible heat fluxes, Bowen ratios and the volumetric water content were compared.

The results demonstrated that the addition of an additive to the growing substrate could increase its water holding capacity significantly. The rise in the amount of water content led to an increase in the cumulative evaporation and the resulting cooling effect. The increase in the water storage also resulted in a reduction in the surface temperature, in addition to prolonging the time, during which the latent heat flux dominated over the sensible heat flux. The study showed that the application of rice husk biochar is not advantageous for green roof energy performance. The increase in biochar concentration in the soil led to the acceleration of plot's drying rate, fast water content depletion and rise in substrate surface temperature, therefore intensified sensible heat transfer. Hence, addressing latent heat release improvement, the study suggests that the hydrogel amendment could be favorably considered to maximize the green roof energy performance.

The investigation of the effects of water retention structures illustrated that they are the most crucial green roof components toward evaporation, latent heat release, and water storage enhancement. Application of the retention structure remarkably intensified evaporation, and thus latent heat release, and notably reduced substrate surface temperature. Among evaluated structures, water

retention plate exhibited the highest potential to contribute to the effective water storage and evaporation enhancement. For water retention plate-equipped plots, latent heat was dominant heat flux throughout almost the entire experiment, therefore provided the highest cooling effect. Furthermore, the study suggests that the incorporation of both superabsorbent polymer additive and water retention structure together has the highest potential to intensify the evaporation effect and provide a considerable surface temperature reduction.

The findings from this study confirmed that the green roof as a system can be optimized toward thermal environment improvement. It is evident that both growing substrate and water retention structures are essential components for the green roof energy performance, thus should be thoroughly considered in the design process. The choice of proper components will result in long-term benefits for both the building and the environment.

Keyword: Biochar; evaporation; green roof; latent heat; superabsorbent polymer; water retention structures; urban heat island.

Student number: 2018-20151

Table of contents

List of tables

List of figures

Chapter 1. Introduction

1.1. Background

The extensive development of urban areas in recent years has resulted in serious changes to the landscape, with vegetation being replaced by buildings and paved surfaces. The replacement of permeable surfaces with dry and impermeable coverage increases heat absorption and decreases water penetration, retention, evaporation, and plant transpiration. Smaller amounts of water available for evaporation and transpiration processes lead to smaller amounts of released latent heat, higher surface temperatures of the ground, and larger amounts of heat released into the atmosphere. These changes are some of the major reasons for cities becoming warmer than their rural counterparts, resulting in a phenomenon called urban heat island (UHI) (Gartland 2008).

The UHIs have a negative impact on human health, air quality, and energy consumption in cities (Wong et al. 2008). It was also reported that urbanization had an effect on precipitation, whereby cities experience fewer and shorter precipitation events than their rural counterparts (Chen et al. 2015). The rise in temperatures in cities, which increases the thermal discomfort and the risk of heat-related diseases, is affected by the sensible heat flux released into the atmosphere. In the case of an impermeable surface, for example, an asphalt road or a concrete roof, the energy received by surface in form of net radiation is partially conducted away through the surface. However, owing to the lack or limited availability of water, a major portion of the incident solar energy is changed into sensible heat. In the case of permeable coverage, where water and vegetation are available, bulk of the solar energy can be dissipated through water vaporization as latent heat and only a small portion will be transformed into sensible heat.

Impermeable surfaces can transform up to 60% of the solar energy into sensible heat, while surfaces saturated with water can convert up to 80% of the solar radiation into latent heat of vaporization (Kravčík et al. 2008). Hence, permeable surface coverage, such as green roofs, which have been gaining popularity as a sustainable building technology with a wide range of benefits (Getter et al. 2006), can be a potential solution for sensible heat flux reduction. The strategies to mitigate UHI through green roofs have become a subject for diverse research studies over the past decade (Rakhshandehroo et al. 2015).

1.2. Motivation

A majority of the previous studies on the thermal regime of green roofs were mainly focused on improving the building's indoor conditions (Parizotto et al. 2011, Jaffal et al. 2012, La Roche et al. 2014). Furthermore, there is a lack of studies that connect evaporation with sensible heat flux reduction toward outdoor environment improvement. Thus, there is a need to further evaluate the green roof's potential in this direction. Also the effects of individual green roof components have not been analyzed in detail; hence, further studies are needed to fill this gap.

1.3. Objectives

The study investigates the potential for improving the green roof toward sensible heat reduction to contribute to UHI mitigation. This research is expected to prove that green roof components can be successfully optimized in order to enhance the evaporation and latent heat transfer. Specific objectives are as follows:

(1) To propose the reactor design for quantifying the heat and energy balance at the green roof.

(2) To evaluate the effects of water absorbent additives to the growing substrate and the application of green roof water retention structures on the evaporation and latent heat transfer.

(3) To propose the design recommendations for the green roofs to optimize the evaporation and latent heat release toward the reduction of sensible heat.

1.4. Research scheme

This research consists of 6 chapters. Chapter 1 contains background, research objectives and research scheme. Chapter 2 presents the literature review. Chapter 3 describes the design of the evaporation reactor, the measurement equipment, and procedures and methods of quantifying the heat and energy balance. Chapter 4 focuses on the experimental results of the effects of soil amendments and water retention structures on green roof evaporation and latent heat transfer. Chapter 5 proposes the design recommendations toward green roof optimization based on the conducted experiments. Chapter 6 summarizes the outcomes of the study and suggests possible further research direction.

Chapter 2. Literature review

2.1. Definition of green roof

Green roofs are surfaces that reproduce soil conditions on building structures (usual roofs of buildings). They compensate for surface losses resulting from the intensive development of the city. The concept of green roofs and their aesthetic and ecological significance for the urban landscape are in line with the concept of sustainable development.

Numerous studies have demonstrated that green roofs not only contribute to UHI mitigation but also improve the air quality (Baik et al. 2012, Pugh et al. 2012) and water quality (Vijayaraghavan et al. 2012, Harper et al. 2015, Zhang et al. 2015), contribute to biodiversity conservation (MacIvor et al. 2011, Madre et al. 2014, Lundholm 2015), and reduce stormwater runoff (Lee et al. 2013, Harper et al. 2015, Zhang et al. 2015). Moreover, a green roof system influences the thermal insulation of the building. Therefore, many researchers have demonstrated the energy-saving potential of green roofs in both laboratory-scale (Ayata et al. 2011, Tabares-Velasco et al. 2011) and field-scale (Feng et al. 2010, Bevilacqua et al. 2016, Peng et al. 2019) studies.

Green roofs are divided into extensive and intensive green roofs. The basis of this division is the type of cultivated vegetation, conditioned by the thickness of the soil substrate layer and the purpose of its use and care. Extensive roofs (low substrate thickness, less than 10–15 cm) are usually conceived as large-surface, with a light and simple structure, using low-demand vegetation. On the other hand, intensive roofs (high soil thickness, more than 15–20 cm) can perform additional utility functions and enrich the space by equipping with paths, roads, playgrounds, fountains, etc. Regardless of the type, all green roofs are used to restore the biologically active surface that was taken for the investment, improving the thermal and climatic conditions of the building, fire protection, and rainwater retention.

2.1.1. Construction of the green roof

Green roofs are most often made as multi-layer systems. Each of the construction layers plays an important role in the structure and completes the whole. A modern green roof consists of thermal insulation, waterproofing membrane, a root resistant protection layer, water retention and drainage, a filter fabric, and finally, a growing substrate and vegetation (Chow et al. 2018).

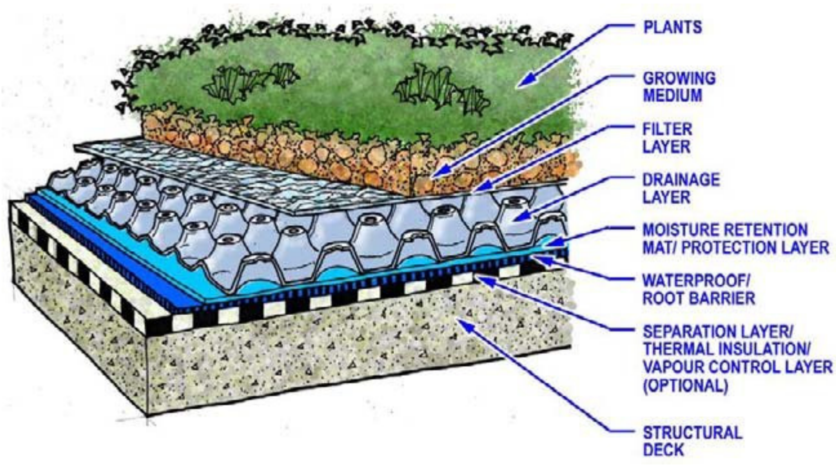


Figure 1. Basic components of a green roof system (Townshend et al. 2007)

Thermal insulation and a waterproofing membrane are a bottom barrier that separates green roof construction from the roof deck. Thermal insulation must be resistant to moisture and temperature changes and mechanically strong, while the waterproofing membrane must be resistant to plant root growth and durable. It should also be characterized by high biological (mold, fungus) and chemical resistance.

The drainage layer is designed to drain excess water during heavy rainfall. It protects soil layers from drying out, provides ventilation to the roots and improves the insulation value of the roof structure. Modern drainage materials also have the ability to store water, hence are often referred to as drainage and retention layer. It is designed to store rainwater and quickly drain its excess to roof drains to prevent roof stagnation and ceiling overload. The most popular solutions are retention plates, drainage mats and granular aggregate layers.

A retention plate (Figure 2), also known as retention panel, is the most commonly used solution in modern green roof technologies due to its lightweight and relatively easy application. A plate is a waffle-shaped module, usually produced with high-strength synthetic or plastic material (polystyrene or polyethylene). Modules are available in different shapes, heights and volume, therefore it is easy to achieve the desired retention capacity. Water is retained within cups, whereas excess water can be gravitationally drained over the edges of the plates or aeration holes and carried off the roof. Hence, the plate is multifunctional: it contributes to water management and provides water available for plant roots. As stored water evaporates, the water eventually returns back to the soil layer. The plate is designed in a way to ensure that there is always a layer of air above it, therefore even during the heavy rainfall plant roots can remain healthy. Moreover, the retention plate is characterized by good permeability to water and drainage does not create a barrier to plant roots. Retention plates might be additionally infilled with granular aggregate for loading support and stability.

Figure 2. Modular retention plate (Cascone 2019)

Drainage mat (Figure 3) has a form of plastic entanglement drainage combined with an integrated or separate thick nonwoven moisture-retaining mat. The sheet flow through the mat depends on density and loft of the entanglement and usually varies from fair to very good. The drainage mat has the ability to move water through capillary action, which helps to alleviate the problem of differences in soil moisture of the roof soil. This type of drainage is applied usually in case of green roofs with the lightest extensive plantings, where the vegetation mats are used without a substrate and the retention and filtration function is fulfilled by many layers of retention geotextile with entangled micro drainage.

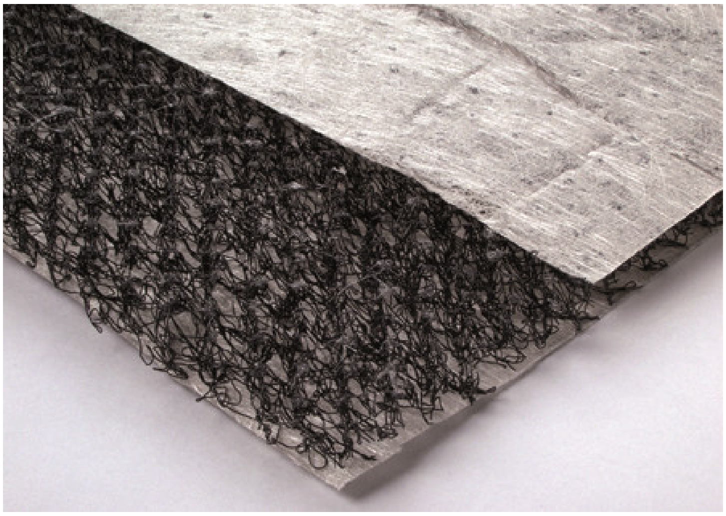


Figure 3. Entangled drainage mat (Bauder.co.uk, 2020)

Granular drainage (Figure 4) is comprised of highly porous granules, allowing natural absorption of water into the material, while providing adequate drainage. The most commonly used materials are: expanded slate, expanded pearlite, expanded clay, pumice, lapilli, pozzolana, and crushed bricks (Cascone 2019). Aggregates are able to transport water through capillary action, although they are usually combined with moisture-retaining mats that enables water to move from the wetter lower levels of the system to drier top levels. Additionally, granular drainage provides a strong environment for root growth.

Figure 4. Granular aggregate (Cascone 2019)

The selection of a type of drainage and water retention layer must be based on such factors as characteristics of the atmospheric precipitation, green roof construction needs and requirements, cost and size of the green roof, expected quantity and flow of rainfall and type of vegetation

The drainage layer is separated from the vegetation layer by filter fabric. A filter prevents the drainage of fine particles that water can carry. It also counteracts the rapid loss of water from the vegetation layer. The filter should be water and vapor permeable, chemically and biologically resistant and mechanically durable. Structural geotextile made of polypropylene is usually chosen for this purpose.

A growing substrate is considered as one of the most important elements of a green roof system, as it provides physical support for the vegetation and supplies water and nutrients for the growth of plants. It consists of mineral and organic components which are selected depending on the type of roof and the planned vegetation. Organic components provide the required nutrition for plants and increase the substrate's water holding capacity. The most popular types of organic fractions are coco-peat, peat moss, pine bark, sawdust, seaweeds, coconut coir, and compost. Mineral components with a properly selected fraction improve water and air properties. Specially selected types of aggregates are characterized by high porosity and water capacity. Most commonly used mineral components are: perlite, vermiculite, zeolite, pumice, crushed bricks, sand, expanded clay, and gravel

The substrates should have adequate porosity and water holding capacity. The ability of substrates to retain water can be increased by reducing the particle size, and therefore increases the amount of inner pore surface of the particles, although this may increase the potential for water acquisition. Properly designed green roof substrate should be light, which is important for the entire roof structure. The thickness of the base layer depends on the type of vegetation used; the substrate should be made of sufficient grain size to ensure that excess water is drained off and the air is collected; must also provide plants with good living conditions. Besides that, green roof substrate should have large water and air capacity, high resistance to cyclic freezing and thawing, be free of physical, chemical and biological impurities, as well as from pathogens. There should be also no floated parts in an amount that can silt the geotextile in the insulating layers and thus cause leaks or rotting of plants.

The growing substrate is also an important component contributing to the evapotranspiration process (the process of evaporation from the soil and transpiration of vegetation). The studies conducted by Djedjig et al. (2012) and Tan et al. (2017) demonstrated that the evapotranspiration process exhibited a strong correlation with the volumetric water content of water in the substrate. In fact, when the water content decreased, both evaporation and transpiration rates were restricted. Feng et al. (2010) found that the growth in the volumetric water content in the growing substrate increased the released latent heat and reduced the stored heat by 24%. Therefore, the evaporative cooling effect can be potentially intensified by optimizing the water holding capacity of the growing substance.

Vegetation on the roof is much more often exposed to adverse environmental conditions, such as strong wind gusts or higher air temperatures. In the case of intensive roofs, when choosing the type of vegetation, it is necessary to consider the specific conditions prevailing in this environment, such as local climate, temperature and wind directions, and take into account the time that later can be devoted to green roof maintenance.

Among those components, three elements, namely the drainage/water retention layer, the growing substrate, and the vegetation layer have the biggest impact on green roof evaporation behavior and the amount of latent heat released.

2.2. Green roof thermal performance

Green roofs combine not only functional and aesthetic values but also have an impact on the thermal efficiency of both the building and the environment.

From a thermal point of view, the benefits of green roofs in the summer season are well characterized in many areas and are the result of evapotranspiration cooling, the insulating properties of the growing substrate and drainage layer, increased albedo and shading by plants. Green roof thermal efficiency was studied by many authors. In this context, Lazzarin et al. (2005) concluded that during the summer period, the green roof with the soil in almost dry conditions allows the reduction of thermal heat gains reaching the underneath room by about 60% compared to the traditional concrete roof with thermal insulation. A study done by Kumar et al. (2005) reviled that green roof can reduce the average indoor temperature by 5.1°C with regard to the bare roof. Field measurements conducted by Onmura et al. (2001) showed that the daytime temperature of the roof stab surface decreased from about 60ºC to 30ºC in the case of a roof loan garden. Many studies have also demonstrated that the layer structure of rooftop greenery can contribute to a cooling effect (Simmons et al. 2008, Takakura et al. 2000, Wong et al. 2003).

2.2.1. The energy balance and Bowen ratio

The energy balance of the green roof, similarly to the traditional roof, is dominated by radiative energy provided by the sun. Solar energy gains are balanced by latent heat flux (evapotranspiration processes from the soil and plant surfaces) and sensible heat flux (convective heat flux), in combination with the conduction of the heat through the soil and roof construction, and thermal longwave radiation exchanged by the substrate and vegetation surface. The energy balance is illustrated in Figure 5.

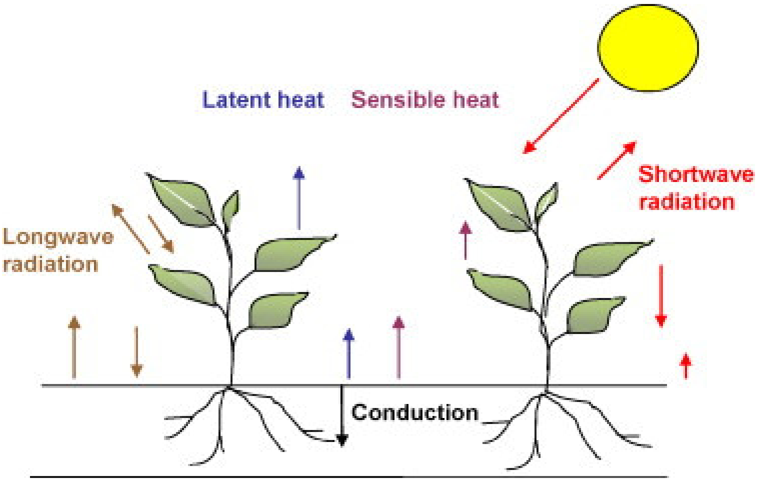


Figure 5. Simplified representation of the energy balance at green roof (Sailor et al. 2008)

In the case of a traditional concrete roof, the energy gains are mainly dissipated in the form of sensible heat, accompanied by surface and air temperature increase. However, studies about the green roof energy balance conducted by Barrio (1998), Theodosiou (2003), and Feng et al. (2010) revealed that for a green roof, the majority of absorbed heat gains are dissipated through evapotranspiration processes.

Latent and sensible heat can be linked together in the form of Bowen ratio (β), which is the ratio of sensible to latent energy flux. Bowen ratio is used to describe how the moist surface responds to a certain amount of net radiation. In a situation where available moisture is low, the amount of released latent heat will be also low and the Bowen ratio value will be greater than one. In the opposite situation, when more moisture in the substrate is available, the latent heat value will be large and the Bowen ratio value will be less than one.

Accordingly, the lower Bowen ratio is, the more latent heat participate in the heat transfer, therefore the higher cooling effect occurs.

Bowen ratio is a simple factor that can be effectively used for the analysis of moist surfaces in terms of their potential toward sensible heat reduction, hence it can be possibly used for comparison of green roof surfaces and their cooling efficiency.

As a result of urbanization, the city experiences a disadvantageous surface energy partitioning, with significant domination of sensible heat flux in urban energy balance. In effect, the Bowen ratios in urbanized areas are greater than unity. The studies on β values showed that a typical average summer daily Bowen ratio can vary from 2.6 in Basel, Switzerland (Christen et al. 2004), 4.16 in Beijing, China (Miao et al. 2012), 4.4 in Marseille, France (Grimmond et al. 2004), to even 5.0 in Melbourne, Australia (Coutts et al. 2007).

To reduce the effect of urban heat island with evaporative cooling, the ideal green roof should have a characteristic similar to rural, vegetated areas and maintain β coefficient below 1.0 value, especially during the summer period. For non-irrigated green roofs during rainless summer periods, this might be challenging to achieve. Tabares-Velasco et al. (2011) in the laboratory-scale green roof experiment has proved that evaporative heat flux decreased along with a decline in the substrate moisture whereas sensible heat flux increased. This shift in energy partitioning has a direct impact on the Bowen ratio. Therefore there has been growing interest in methods of increasing green roof water absorbance and water storage capability.

2.3. Soil amendments in green roof

Increasing the amount of smaller particles in the growing substrate, in order to maximize water retention capacity, can have a negative impact on drainage quality and maintenance, since the smallest particles can potentially pass through filter fabric. Recent studies have suggested that the water holding capacity of a green roof substrate can be also successfully increased by using soil amendments.

One of the most popular groups of amendments commonly used in the agriculture are super absorbent polymers (SAP), also known as hydrogels (Farrell et al. 2013, Marin et al. 2014). The hydrogels are widely available, artificial water retention additives to the soil used in landscaping, agriculture, horticulture, and forestry. They are characterized by an ability to absorb and store water hundreds of times their weight (Johnson 1984). The study conducted by Abedi-Koupai et al. (2008) showed that application SAP in an amount of 8 g/kg in the soil can increase the available water content 1.8 times in clay and 2.2 to 3.2 times in loamy and sandy loamy soils, respectively. Montesano et al. (2015) have found that by amending sandy soil with 2% w/w of hydrogel, the soil moisture at field capacity can be increased up to 400% compared to non-amended soil. Hence, they can potentially increase the evaporative cooling effect and latent heat release.

Another promising groups of additives are biochars. Biochars are carbonized biomass with plenty of benefits as a natural soil amendment (Glaser et al. 2002, Major et al. 2010, Zhenyu et al. 2013). Studies suggest that biochar can have the ability to retain water (Mulcahy et al. 2013, Bruun et al. 2014). The experiment carried out by Beck et al. (2011) showed that amending soil with biochar increased soil water retention by approximately 4.4% in comparison to non-treated soil. Thus can potentially improve the substrate's water holding capacity and therefore contribute to sensible heat flux reduction.

Chapter 3. Evaporation reactor design for quantifying the heat and energy balance at the green roof

3.1. Evaporation reactor design

A specially designed evaporation reactor (Figure 6 and Figure 7) was used to carry out the evaporation experiment. The reactor consisted of a transparent acrylic tubular cover, placed on a stand at an angle to allow the gravitational flow of condensed water to the condensate drain. The tubular cover was tightly closed to prevent any moisture loss to the surroundings and eliminate the wind effect on the evaporation. The reactor dimensions were 800 mm in length and 400 mm in diameter.

Figure 6. Photography of the evaporation reactor setup.

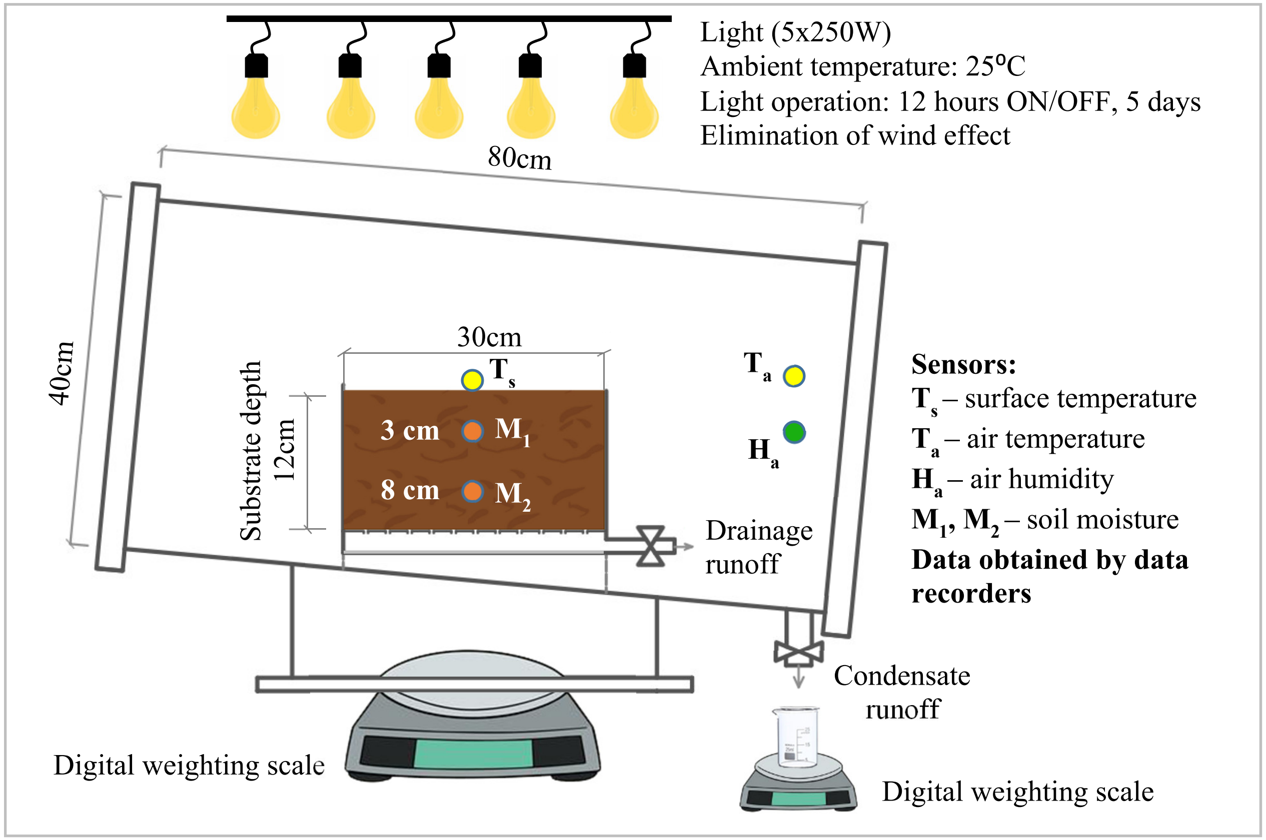


Figure 7. Schematic of the evaporation reactor with measurement points.

The experimental plot was placed in an acrylic box with a surface area of 0.3 × 0.21 m^2. The box structure contained from the top to the bottom, a 12-cm layer of the evaluated substrate, a nonwoven fabric (for soil loss prevention), a perforated acrylic plate (for drainage), and a 4-cm removable drainage space connected to a drainage runoff.

Within each substrate layer, two time-domain reflectometers (TDRs) soil moisture sensors (VWC T3, Transducer System Electronic, Figure 8) were installed, one in the top layer (at a depth of 3 cm) and the other in the bottom layer (at a depth of 8 cm) (Figure 6). Prior to the commencement of each experiment, the acrylic box with the investigated plot was exposed to a 1-h long simulated rainfall event at a rate of 60 mm/h (based on the five-year frequency probability of rainfall intensity in Seoul, South Korea), using a pre-prepared rainfall simulation site. After watering, the drainage runoff was opened and the sample was left for 24 h in order to allow the natural drainage of the excess water. After the runoff flow stopped occurring, the drainage runoff was closed and the sample was placed in the reactor. Closing of the drainage runoff valve was based on the real green roof system maintenance practice, where usually runoff is closed during a non-rainy period and temporarily opened after the occurrence of heavy rainfall.

Figure 8. TDR sensor VWC T3 (Soilnwater.com, 2020)

The solar radiation was simulated using five UV-A bulbs, fixed on a stand above the experimental site. The radiation emitted by the bulbs was measured using a solar power meter (DT-1307, Shenzhen Everbest Machinery Industry Co., Ltd.) and varied between 600 and 700 W/m^2, which is a typical measure of the solar radiation achievable on a sunny day. The lamps were operated at 12-h intervals to simulate day and night conditions (lights on and off).

The radiative heat would be absorbed by the substrate and the water in the soil would evaporate. As a result, the density of the humid air would increase and moisture would condense on the inner surface of the transparent cover. Consequently, the condensed water would naturally flow towards the bottom of the tubular cover, aided by the gravitational force, and then would be discharged by the condensate drain at the lower end of the cover to the condensate storage glass. The changes in both the reactor water and the condensed water were measured by two separate digital balances at 30-min intervals.

Figure 9. Thermocouple K-type for high temperatures and USB temperature transmitter UA11-CKS (Radionode365.com, 2020)

Thermocouples (Figure 9) were placed inside the reactor to measure the substrate surface temperature and the air temperature inside the reactor with at 1-min intervals with an accuracy of ±0.1 ºC. All the thermocouples were shielded with aluminum foil to eliminate the effect of radiation on the temperature measurements. The temperature was acquired by the thermocouple temperature transmitter via USB (UA11-CKS, Radionode) and recorded by PC recording software (Tapaculo Lite, Radionode). Additionally, the air humidity inside the reactor was measured using a humidity meter with an accuracy of ±1.0% RH. A stable condition of the surroundings during the experiment was ensured (26 °C ambient temperature and 50% relative humidity).

The substrate moisture content was recorded every 10 seconds throughout the experimental period using a data logger (DT80 dataTaker Data Logger, Thermofisher Scientific Inc.). All measured parameters were used for the evaluation of evaporation and energy analysis.

The proposed evaporation reactor enables relatively easy measurements of the parameters essential for evaporation investigation and energy analysis in the controlled environment.

3.2. Method of quantifying the heat and energy balance

Energy analysis involved the calculation of two heat fluxes: latent heat flux (Q_L) and sensible heat flux (Q_s), and as a result Bowen ratio (β). Latent heat flux is expressed as (Huang et al. 2011):

$$Q_L = \frac{M_{ev}}{t} L_v \qquad \textit{eq.1}$$

Where,

Q_L : latent heat flux (kW/m$^{2)}$,

M_{ev}: mass of evaporated water (g/m^2),

L_v : specific latent heat of vaporization (MJ/kg),

t : evaporation time (s).

Sensible heat was estimated as (Huang et al. 2011):

$$Q_S = \Delta T \cdot h \qquad \textit{eq.2}$$

Where,

Q_S : sensible heat flux (kW/m^2),

ΔT : temperature difference between substrate surface and air (K),

h : convection heat transfer coefficient (kW/m^2K), determined in accordance with ASHRAE (ASHRE 2017).

As a final result, Bowen ratio (β) was calculated as:

$$\beta = \frac{Q_S}{Q_L} \qquad eq.3$$

During the drying process, the amount of water available in the substrate for evaporation gradually decrease, which results in a shift from the domination of latent heat release toward more intense sensible heat release. Calculation of both heat fluxes through the time allows us to compare the time duration of intensive evaporation between the samples and points out when sensible heat starts to surpass the latent heat release, therefore when the passive cooling effect starts to decrease. By connecting both fluxes in the form of simple factor, like the Bowen ratio, it is possible to compare very easy the moist surfaces in terms of efficiency of evaporation and latent heat release.

Chapter 4. Evaluation of the effects of soil amendments and water retention structures on evaporation and latent heat transfer from the green roof

4.1. Characteristic of soil amendments

The biochar chosen for this study was a rice husk biochar (Yougi Ind.Co., Yoogi Biochar, Figure 10), carbonized at 400-500ºC. Specific surface area, total pore volume and average pore diameter of the additive were determined using Brunauer, Emmett and Teller (BET) method of adsorption of nitrogen gas (MicrotracBEL Corp., BELSORP-mini). The results are presented in Table 1.

Figure 10. Rice husk biochar.

Table 1. Biochar characteristic determined by BET method.

Specific surface area, m^2/g	Total pore volume, cm^3/g	Average pore diameter, nm
2.57	$1.22 \cdot 10^{-2}$	19

The chosen superabsorbent additive (SAP, hydrogel) was sodium polyacrylate (Jeije Co., Super Absorbent Polymer, Figure 11). The water holding capacity of both amendments was experimentally determined by immersion of the additive samples in the distilled water for 12 hours, natural filtration of the slurry and 24h of oven drying. The amount of retained water was calculated as a difference in weight between a swollen sample and an oven-dried sample. The summary of the amendments' water holding capacity is summarized in Table 2.

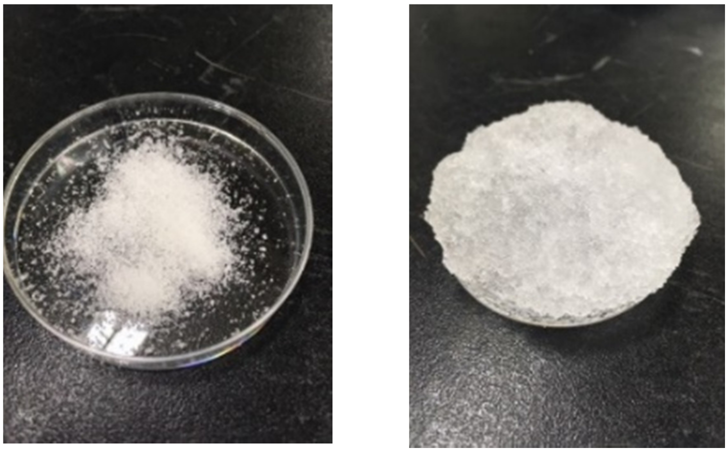


Figure 11. Sodium polyacrylate (hydrogel) in the powder form (left picture) and after contact with water (right picture).

Table 2. Water holding capacity of soil amendments.

Saturation time	Drying conditions	Additive	Retained water ($g\ H_2O/g$ additive)
12 h	105 ºC 24 h	Biochar	6.9
		Hydrogel	307.8

4.2. Characteristic of water retention structures

Three water retention structures were selected to evaluate their influence on the evaporation and latent heat release from the green roof: granular layer, retention mat, and the retention plate. All the selected components are in common use in green roofing infrastructure.

The aggregate chosen for the granular layer was the bottom ash lightweight aggregate (BLA). Bottom ash is a porous waste produced in a coal boiler and can be often found in the coal-fired power plants and thermal power stations. It is considered to be highly recyclable, used widely to increase the strength of such materials as concrete (Karasu et al. 2007). Due to its economical and eco-friendly properties, bottom ash lightweight aggregate became a study interest in the environmental field, especially for its water absorption properties. The characteristic of BLA material used in the experiment is summarized in Table 3.

Table 3. Physical characteristic of granular aggregate (Chung 2019).

Particle size	Porosity	Absorption	Specific gravity
~25mm	4.39	3.85	1.23 g/cm^3

Water retention mat applied for the experiment consisted of entangled plastic structure and two layers of thick non-woven geotextile mat, covering both sides of the structure. The chosen water retention plate was a standard plastic waffle-shaped board with water retention pockets. The plate was 4cm high, the diameter of the pockets was 7cm, and the space interval between pockets was 10cm.

All the structures varied in water retention capacity, weight, load capacity, and load-settlement behavior. The characteristic is summarized in Table 4.

Additionally, to evaluate the combined effect of the water-absorbent additives and water retention structures, the water retention plate was chosen to be evaluated together with hydrogel amended substrate in order to investigate the possible optimization of the evaporation and latent heat release.

Table 4. Characteristic of water retention structures.

Structure	Granular layer	Retention mat	Retention plate
Height	4cm	4cm	4cm
Water retention capacity	409 ml	577 ml	750 ml
Weight (per m^2)	34.89 kg/m^2	5.91 kg/m^2	1.64 kg/m^2
Load-settlement behavior	Does not deform easily, can possibly settle	Easily deforms and settles	Does not deform easily and does not settle

4.3. Experimental set-up

Laboratory-scale experiments were conducted in an evaporation reactor to investigate the surface temperature changes, soil moisture variations, evaporation and latent heat transfer based on different types and concentrations of soil amendments. All the experiments were carried out in indoor conditions.

The selected substrate was a commercially available lightweight soil (Seoul Bio, Biogreen soil), used in landscaping and rooftop farming. The bulk density of the substrate was 0.2g/cm^3. Particle size distribution is presented in Figure 12. The soil consisted of 17% of inorganic particles and 83% of organic matter. The composition of the substrate is listed in Table 5.

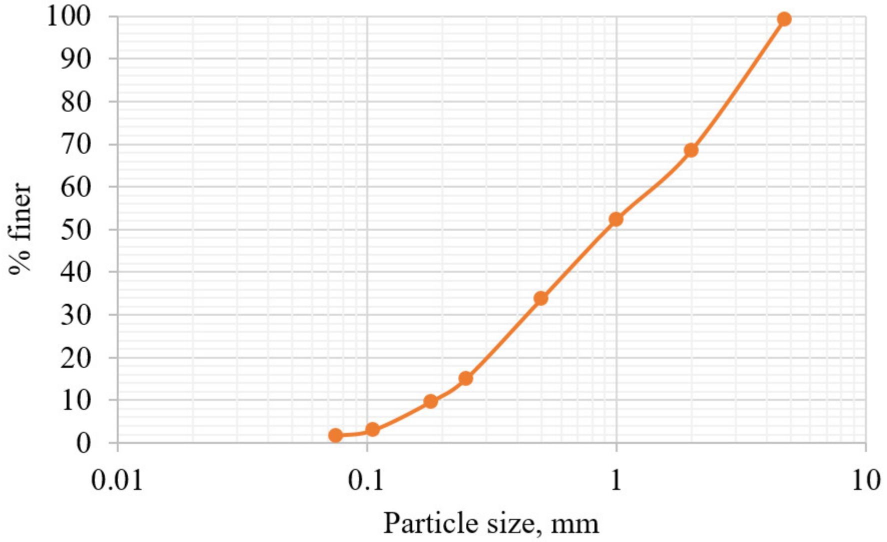


Figure 12. Growing substrate particle size distribution.

Table 5. Composition of the substrate.

Composition	Volume
Coco peat	68.0%
Peat moss	14.7%
Perlite	7.0%
Zeolite	4.0%
Vermiculite	6.0%
Fertilizer	0.3%

In total, evaluated experimental plots were: one non-treated soil-only sample prepared as control plot, four hydrogel-treated plots with polymer concentration: 0.3%, 0.6%, 0.8% and 1.0% w/w, four biochar-treated plots with biochar concentration: 1.0%, 1.5%, 2.5% and 5.0% w/w, and four samples equipped with water retention structures: a sample with retention mat, a sample with granular layer, sample with retention plate and sample with retention plate combined with the addition of 0.6% w/w of hydrogel to the growing substrate. The complete plot set-up is summarized in Table 6. The initial soil water content within all the evaluated plots varied between 2% and 3% (dry substrate).

Table 6. Set-up of the experimental plots.

Plot set-up	**Name**	**Set-up**
Bare soil plot	Control	Soil
Hydrogel-amended plots	H0.3%	Soil with 0.3% w/w hydrogel addition
	H0.6%	Soil with 0.6% w/w hydrogel addition
	H0.8%	Soil with 0.8% w/w hydrogel addition
	H1.0%	Soil with 1.0% w/w hydrogel addition
Biochar-amended plots	B1.0%	Soil with 1.0% w/w biochar addition
	B1.5%	Soil with 1.5% w/w biochar addition
	B2.5%	Soil with 2.5% w/w biochar addition
	B5.0%	Soil with 5.0% w/w biochar addition
Plots with water retention structures	GL	Soil with a granular layer
	RTM	Soil with a retention mat
	RTP	Soil with a retention plate
	RTP + H	Soil with 0.6% w/w of hydrogel and a retention plate

4.4. Results and discussion

4.4.1. Soil amendments

Figure 13 and Figure 14 show the evolution of temperature at the substrate surface of all the plots. After the lamps were turned on, the surface temperature gradually increased until the end of the day, significantly dropped after the lamps were turned off, and then gradually decreased through the night up to the ambient temperature level.

The results demonstrated that in all the cases, the surface temperature stayed relatively stable during the first two days of the experiment owing to intense evaporation. Moreover, when the water content in the top layer was relatively high, the evaporative cooling effect was also high. Subsequently, the temperature started to significantly rise during a simulated daytime. This increase continued util the end of the experimental period. The difference in the substrate surface temperature between the end of the first day (day 1) and the last day of the experiment (day 5) varied between 27 and 32 °C. The results prove the significant effect of evaporative cooling from the substrate on its surface temperature.

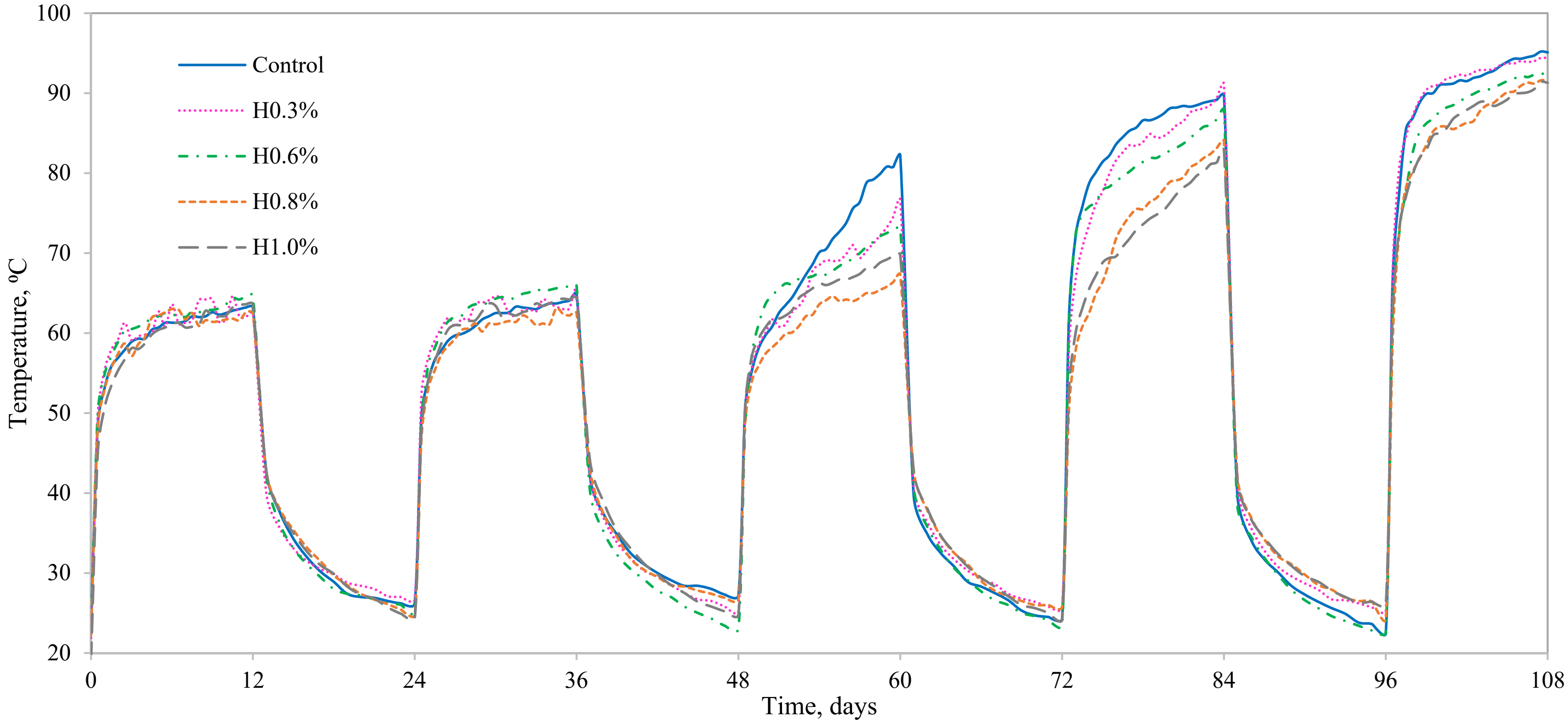


Figure 13. Variations of the substrate surface temperatures with time for hydrogel-treated plots.

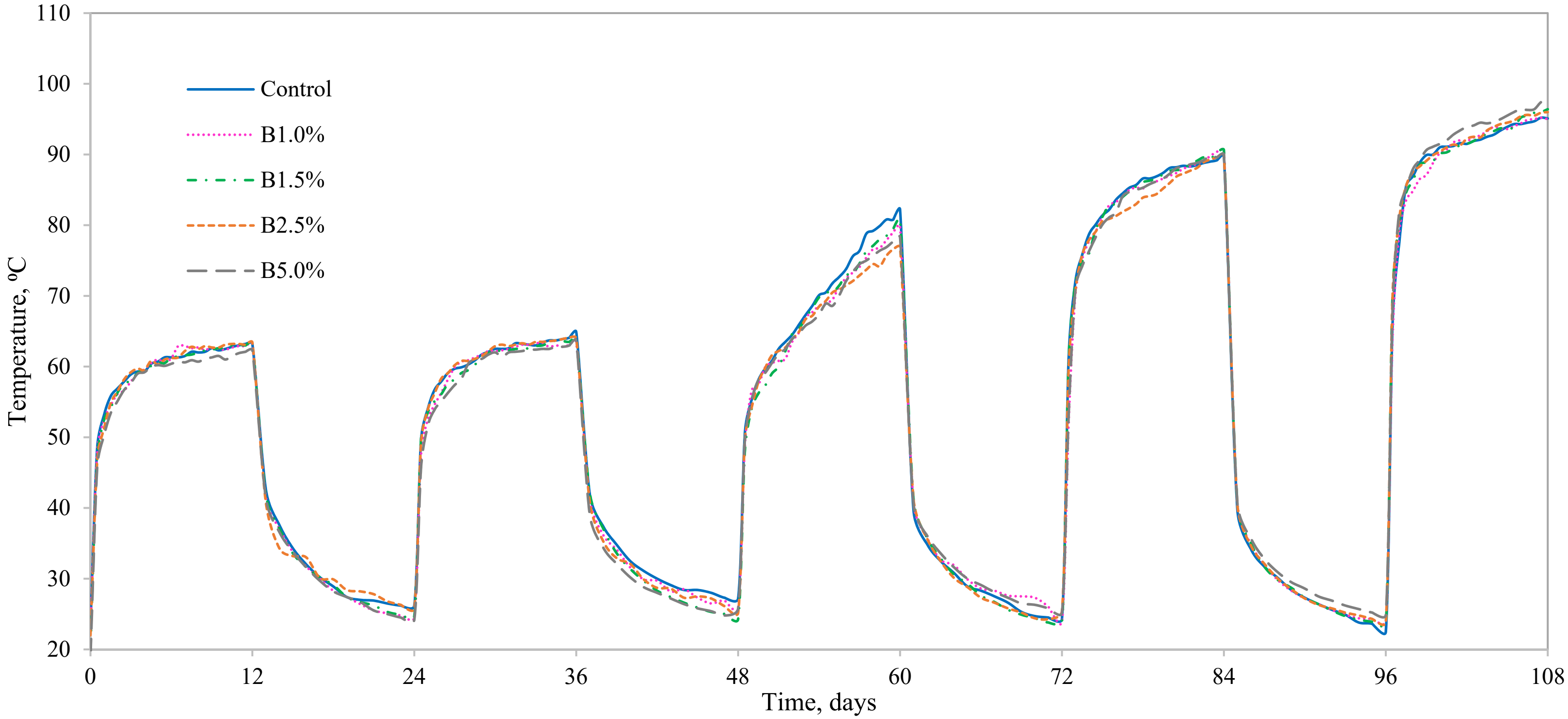
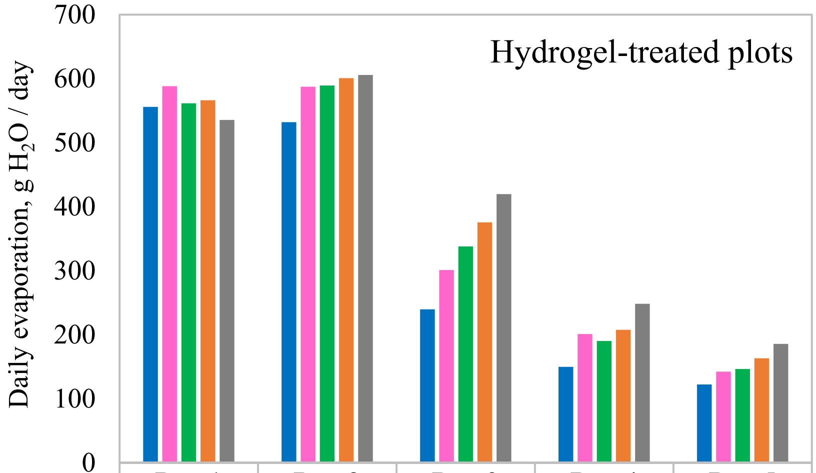


Figure 14. Variations of the substrate surface temperatures with time for biochar-treated plots.

It was observed that during the first two days of the experiment, all the samples showed similar surface temperatures; subsequently, it was noticed that the samples with the polymer amendment maintained lower surface temperatures when compared to the biochar-treated samples and control plot. The pattern of the temperature rise through the experimental period suggested that the surface temperature became lesser as the hydrogel concentration in the substrate was increased. Additionally, the plots with the highest concentration of the polymer maintained lower surface temperatures for a longer time. Plots H1.0% and H0.8%, for the first two days, exhibited comparable surface temperatures as the rest of the samples; however, during days 3 and 4 they demonstrated noticeably lower temperatures compared to the other plots. It can be concluded that water present in the substrate has a major effect on the substrate surface temperature.

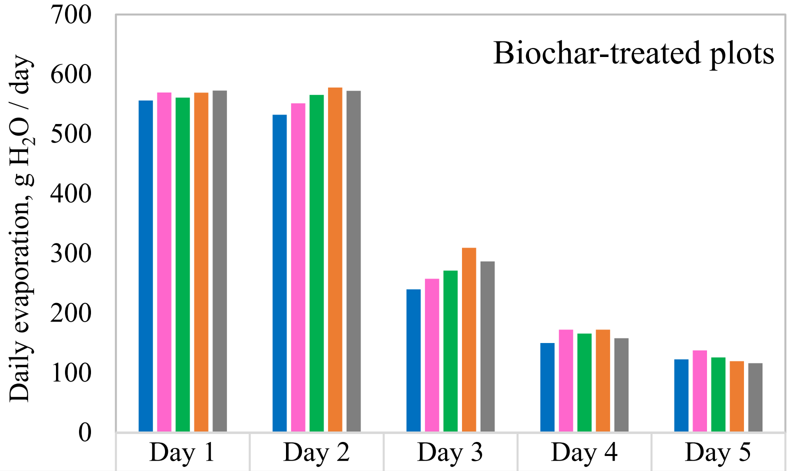
In the case of biochar-treated plots and control plot, the surface temperature rise proceeded faster, caused by lower water content, and therefore less intense evaporation. There was no significant difference in the surface temperature between the samples with biochar additive and control plot.

Figure 15 and Figure 16 show daily evaporation and Figure 17 and Figure 18 illustrate the cumulative evaporation for all the plots through the experimental period. It was observed that the overall evaporation patterns in all the samples were similar. The evaporation occurred intensely during the daytime, when solar energy (simulated by the lamps) was provided. Subsequently, it slowed down significantly owing to the energy limitation and the high relative air humidity inside the reactor. The amount of water evaporated during the night was very low and varied between 40 g in 12 h (on the first night) and 7 g in 12 h (on the last night). Therefore, the night-time water evaporation was assumed to be negligible. The evaporation proceeded at the fastest rate during the first two days of the experiment, when the surface of the substrate was relatively wet; subsequently, as the surface dried further, the evaporation gradually started to reduce.



	Day 1	Day 2	Day 3	Day 4	Day 5
Control	556	532	240	150	122
H0.3%	588.3	587.4	301.1	201.2	142.4
H0.6%	561.6	589.3	338.1	190.3	146.6
H0.8%	566.3	600.8	375.6	207.8	163.3
H1.0%	535.6	605.8	419.8	248.4	185.8

Figure 15. Daily evaporation of hydrogel-treated plots.



	Day 1	Day 2	Day 3	Day 4	Day 5
Control	556	532	240	150	122
B1.0%	569.4	551.3	257.4	172.2	137.5
B1.5%	560.8	565.4	271.1	165.6	125.7
B2.5%	569.0	577.7	309.2	172.3	119.4
B5.0%	572.6	572.2	286.5	157.9	116.0

Figure 16. Daily evaporation of biochar-treated plots.

It was noted that during the first 48 h of the experiment, all the evaluated samples evaporated comparable amounts of water. Subsequently, in the case of plots with soil amendments, the evaporation rate started to steadily slow down. The total amount of evaporated water was the highest for hydrogel-treated plots: H1.0% (2.12 kg), followed by H0.8%, H0.6%, and H0.3% (2.03, 1.95, and 1.90 kg, respectively). For biochar-treated plots, the highest amount of evaporated water was noted in the case of plot B2.5% (1.83 kg), followed by B5.0% (1.79 kg) and B1.5% with B1.0% (both 1.78 kg). The smallest amount was evaporated from the control plot (1.67 kg).

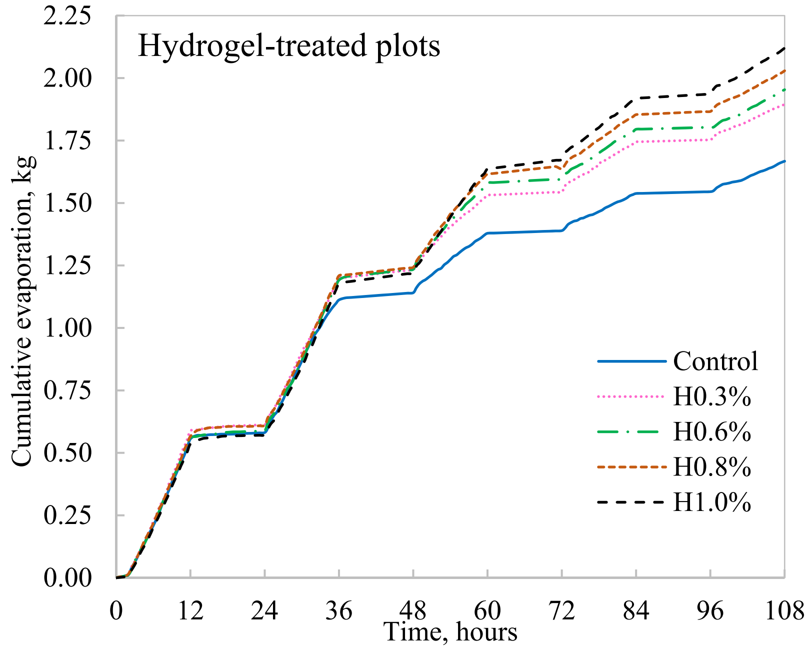


Figure 17. Cumulative evaporation of hydrogel-treated plots.

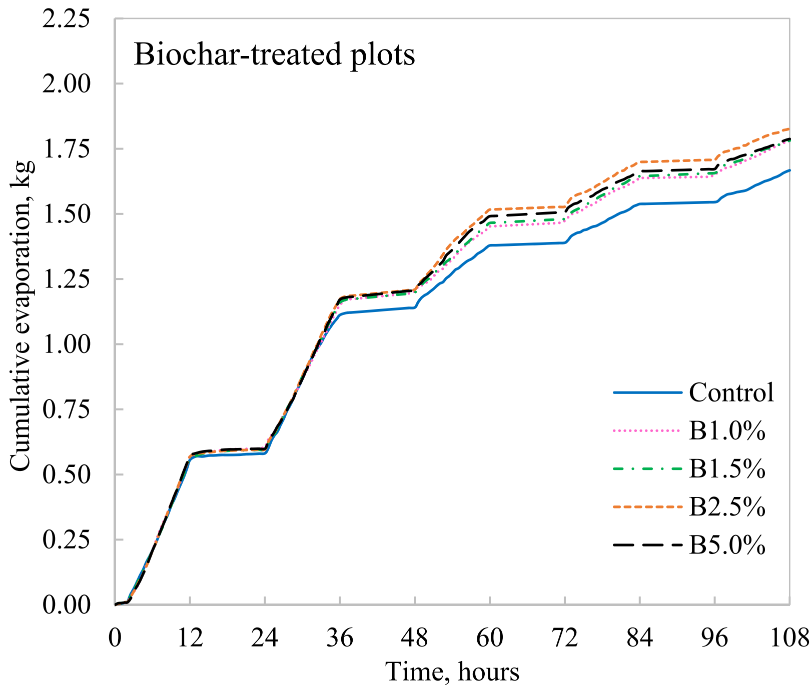


Figure 18. Cumulative evaporation of biochar-treated plots.

In the case of plots with a polymer amendment, the cumulative evaporation increased as the hydrogel concentration in the soil was increased. An addition of 1.0% w/w of the polymer increased the amount of evaporated water by 0.45 kg compared to the sample without the polymer treatment. However, even the smallest examined concentration of the hydrogel noticeably raised the evaporation effect; for example, an addition of 0.3% of the hydrogel increased the evaporation by 0.23 kg. It can be concluded that in this case, the addition of polymer to the soil resulted in significantly higher evaporation.

Biochar-treated samples evaporated noticeable less water than hydrogel-treated samples, however, those amounts were still higher compared to the control plot. Unlike in the case of hydrogel-treated samples, there was no increase in the total amount of evaporated water with an increase of biochar concentration.

The variations of latent and sensible heat fluxes for all the experimental plots are shown in Figure 19, Figure 20, and Figure 21. It was observed that for all the investigated plots, the latent heat of vaporization significantly dominated over sensible heat during the first three days of the experiment. This domination was an effect of the intense evaporation caused by high water content in the substrates, especially the top layer. Subsequently, a distinct growth in the sensible heat flux was noted owing to the restriction on the evaporation.

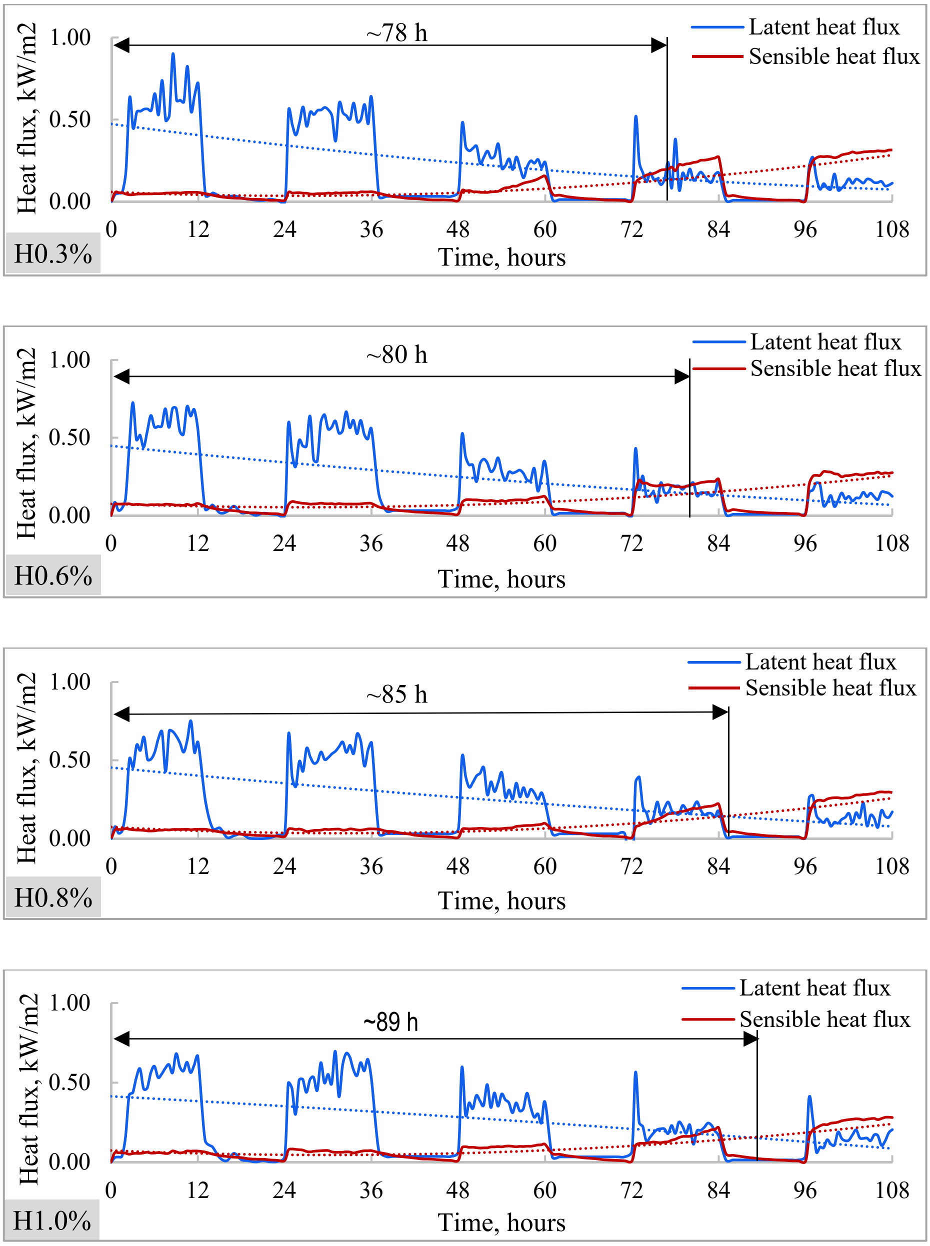


Figure 19. Variations in the latent and sensible heat fluxes, and the time of latent heat flux domination for hydrogel-treated plots.

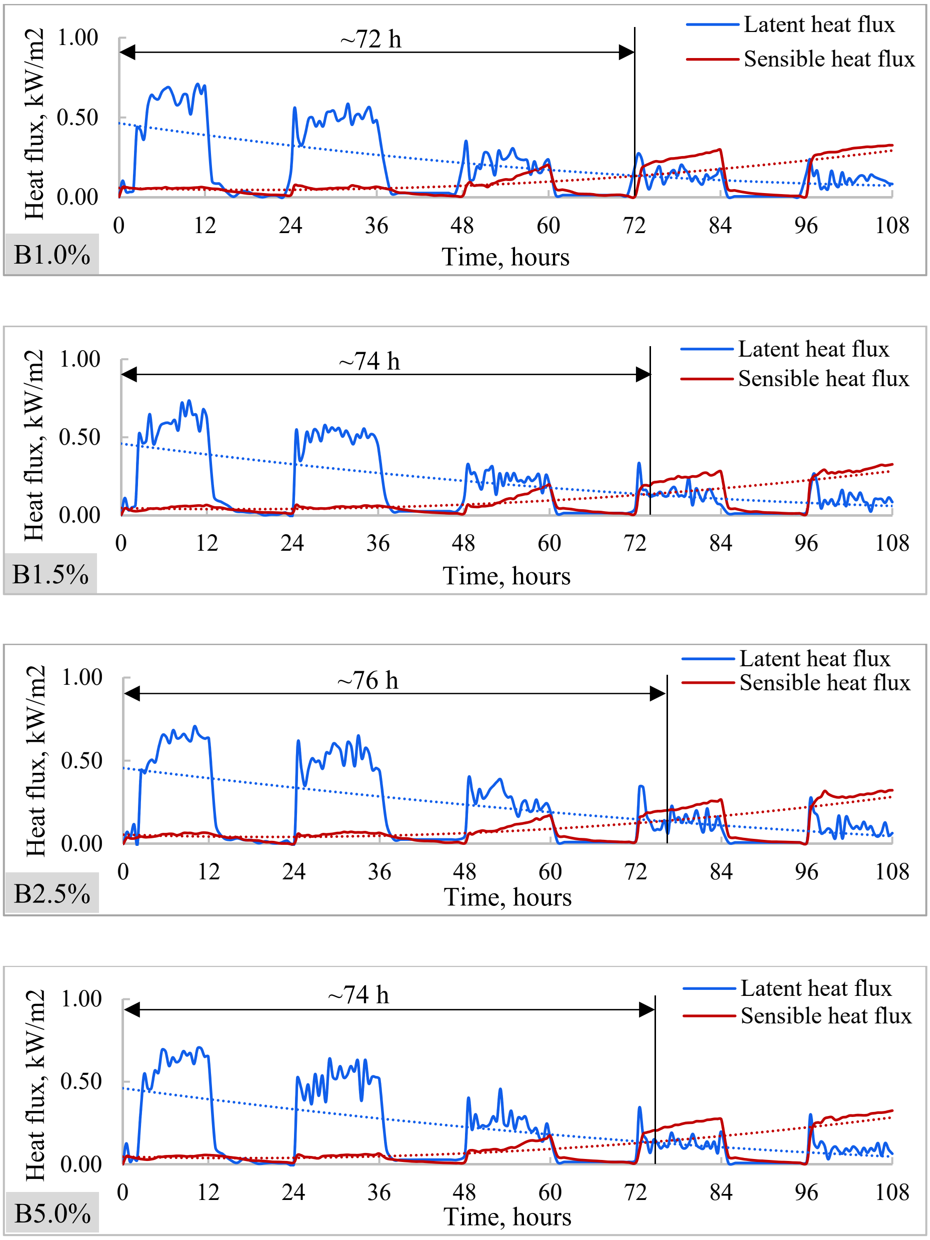


Figure 20. Variations in the latent and sensible heat fluxes, and the time of latent heat flux domination for biochar-treated plots.

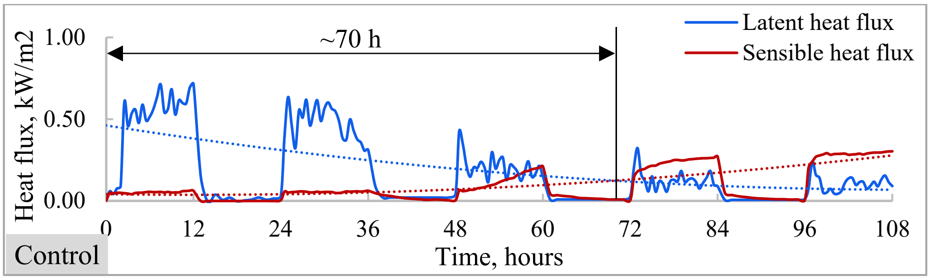


Figure 21. Variations in the latent and sensible heat fluxes, and the time of latent heat flux domination for the control plot (non-treated plot).

In the case of hydrogel-treated samples (Figure 19), the time for which the latent heat surpassed the sensible heat increased with an increase in the polymer additive concentration in the substrate. In comparison to the sample without the amendment (control plot), the domination time was prolonged for 8, 10, 15, and 19 h for plots H0.3%, H0.6%, H0.8%, and H1.0%, respectively. The addition of polymer to the substrate noticeably increased the time, during which the latent heat of vaporization exceeded the sensible heat, and thereby reduced the surface temperature. Hence, the SAP-treated substrates have the potential to not only contribute to the UHI mitigation but also reduce the building cooling loads.

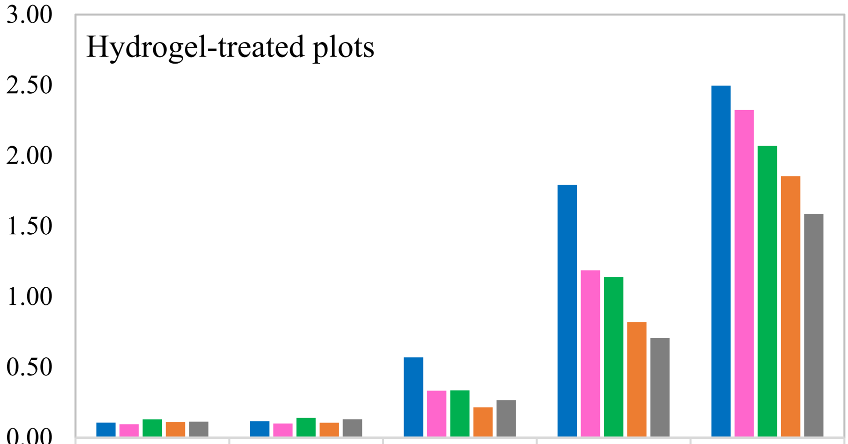
For samples with biochar amendment (Figure 20), the increase in biochar concentration did not prolong significantly the time of latent heat dominance. The longest prolongation was observed for plot B2.5% (4 h in comparison to the control plot). Interestingly, the time in which latent heat surpassed the sensible heat did not increase with the increase of biochar concentration. Plot B5.0% with the highest additive content achieved same time prolongation as plot B1.5% (2 h prolongation).

The shortest latent heat domination time was observed for the control plot (Figure 21), where the latent heat flux was lower than the sensible heat by the end of day 3 (~ 62 h). This was as a result of the restriction on the evaporation imposed by the limited soil moisture.

The latent and sensible heat flux calculations allow the evaluation of the Bowen ratios (ratio of sensible heat to latent heat) for the experimental plots. As the evaporation during the night time was negligibly low, the estimated Bowen ratios were based only on the daytime fluxes. The assessed Bowen ratios are shown in Figure 22 and Figure 23.

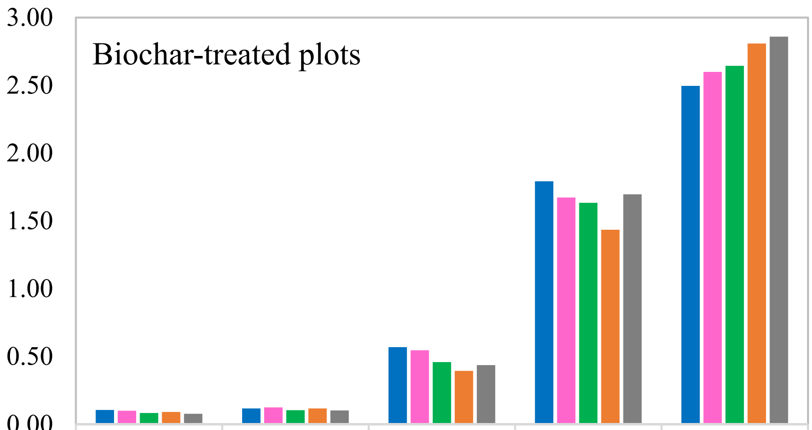
It was observed that during the first three days of the experiment, owing to the intense evaporation, the Bowen ratios of all the samples remained below 1.0, which indicates the predominance of the latent heat of vaporization over the sensible heat. The Bowen ratios during days 1 and 2 for all the plots were comparable. They indicate that during the first two days, the evaporation was not restricted and occurred at a similar rate for all the plots.

The highest Bowen ratios occurred for the control plot. The control plot exhibited the lowest moisture content in the top layer of the substrate, where the highest evaporation restriction existed, and therefore witnessed the highest latent heat flux restriction.



	Day 1	Day 2	Day 3	Day 4	Day 5
Control	0.11	0.12	0.57	1.79	2.50
H0.3%	0.10	0.10	0.33	1.19	2.32
H0.6%	0.13	0.14	0.33	1.14	2.07
H0.8%	0.11	0.11	0.22	0.82	1.85
H1.0%	0.11	0.13	0.27	0.71	1.59

Figure 22. Daily average Bowen ratios for hydrogel-treated plots.



	Day 1	Day 2	Day 3	Day 4	Day 5
Control	0.11	0.12	0.57	1.79	2.50
B1.0%	0.10	0.12	0.55	1.67	2.60
B1.5%	0.08	0.10	0.46	1.63	2.64
B2.5%	0.09	0.12	0.39	1.44	2.81
B5.0%	0.08	0.10	0.44	1.70	2.86

Figure 23. Daily average Bowen ratios for biochar-treated plots.

The lowest Bowen ratio occurred for the samples with the highest hydrogel concentration (Figure 22). For plots H1.0% and H0.8%, the Bowen ratios stayed under 1.0 for the first four days of the experiment and below 2.0 on the last day of the experiment (1.59 and 1.85, respectively). With an increase in the polymer concentration, the Bowen ratios during days 3–5 stayed lower than in the case of the plots without the polymer treatment. This confirms that the amendment increased water availability and prolonged the time, during which intense evaporation occurred, thereby extending the time, during which sensible heat flux was dominated by the evaporative cooling effect.

In case of biochar amendment (Figure 23), the Bowen ratio values stayed slightly lower compare to control plot, however during last day of the experiment (day 5) Bowen ratio of all biochar-treated samples surpassed the value achieved by control plot, with the most significant growth in case of the highest additive concentrations (B2.5% and B5.0%). It implies that an increase in the amount of biochar additive in the substrate may accelerate the drying process of the plot.

Table 7 shows the amount of water remaining after the drainage. It was observed that the plots with soil amendments had higher amounts of remaining water compared to the control plot. Moreover, the highest amount of remaining water was noted for hydrogel-treated plots and it increased with the dosage of the added polymer.

Table 7. Amount of water in the substrate remained after drainage.

Plot	Remaining water (mm)
Control	35.7
B1.0%	36.9
B1.5%	37.6
B2.5%	39.7
B5.0%	39.7
H0.3%	46.5
H0.6%	48.8
H0.8%	55.1
H1.0%	58.9

The variations in the moisture content of the substrates for a five-day period at two different depths (3 and 8 cm) are shown in Figures 24 and Figure 25, respectively. The plots with the polymer amendment displayed higher initial water contents at both the depths compared to the other plots. This trend was similar to that of the remaining water presented earlier. It was caused by a rise in the water holding capacity of the substrates by the addition of the hydrogel. Samples treated with biochar had slightly higher initial water content than control plot at the bottom layer, when in the top layer the achieved initial water contents were comparable.

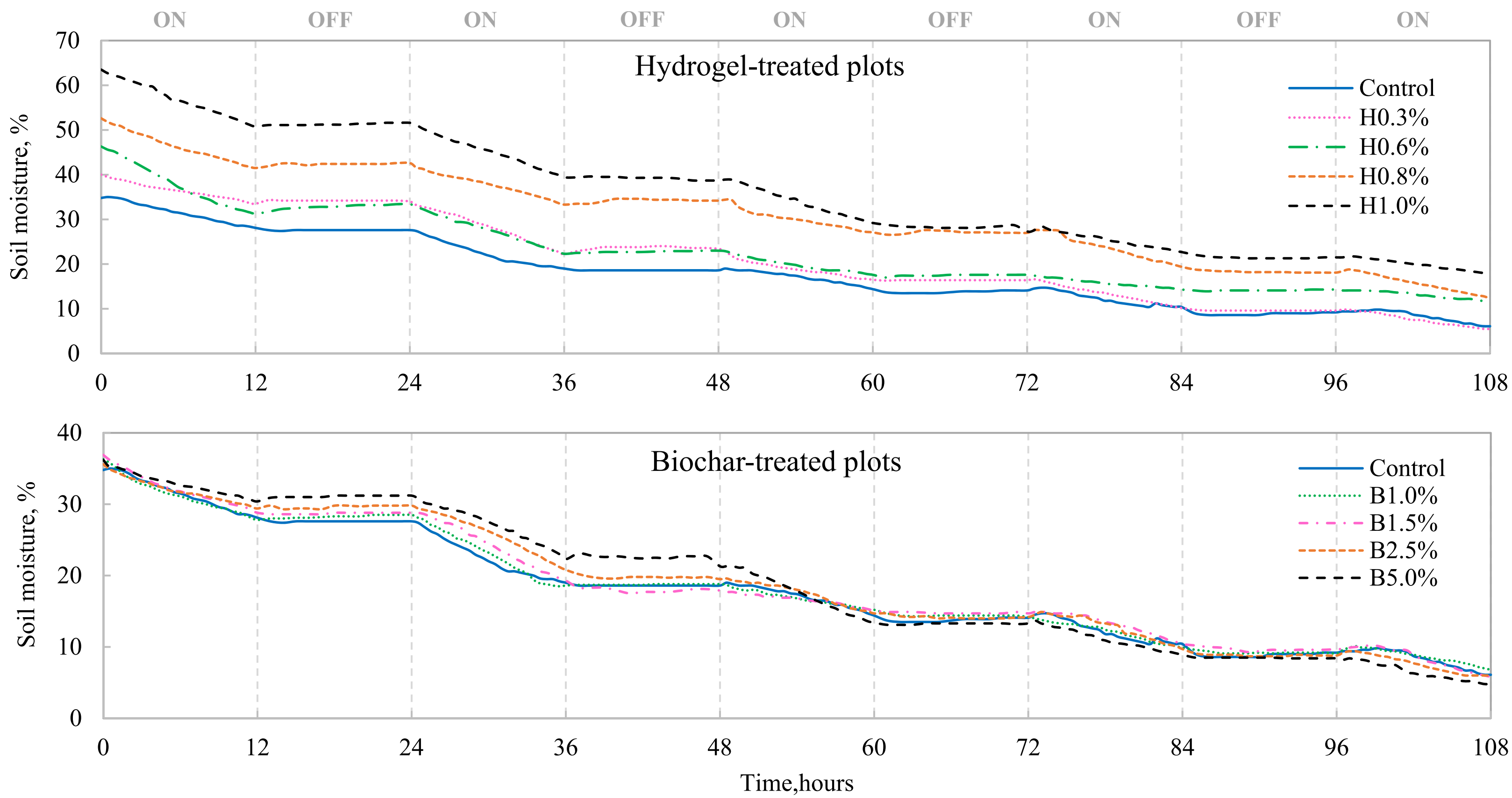


Figure 24. Variation in the water content in the substrates at 3-cm depth with time for hydrogel and biochar-treated plots.

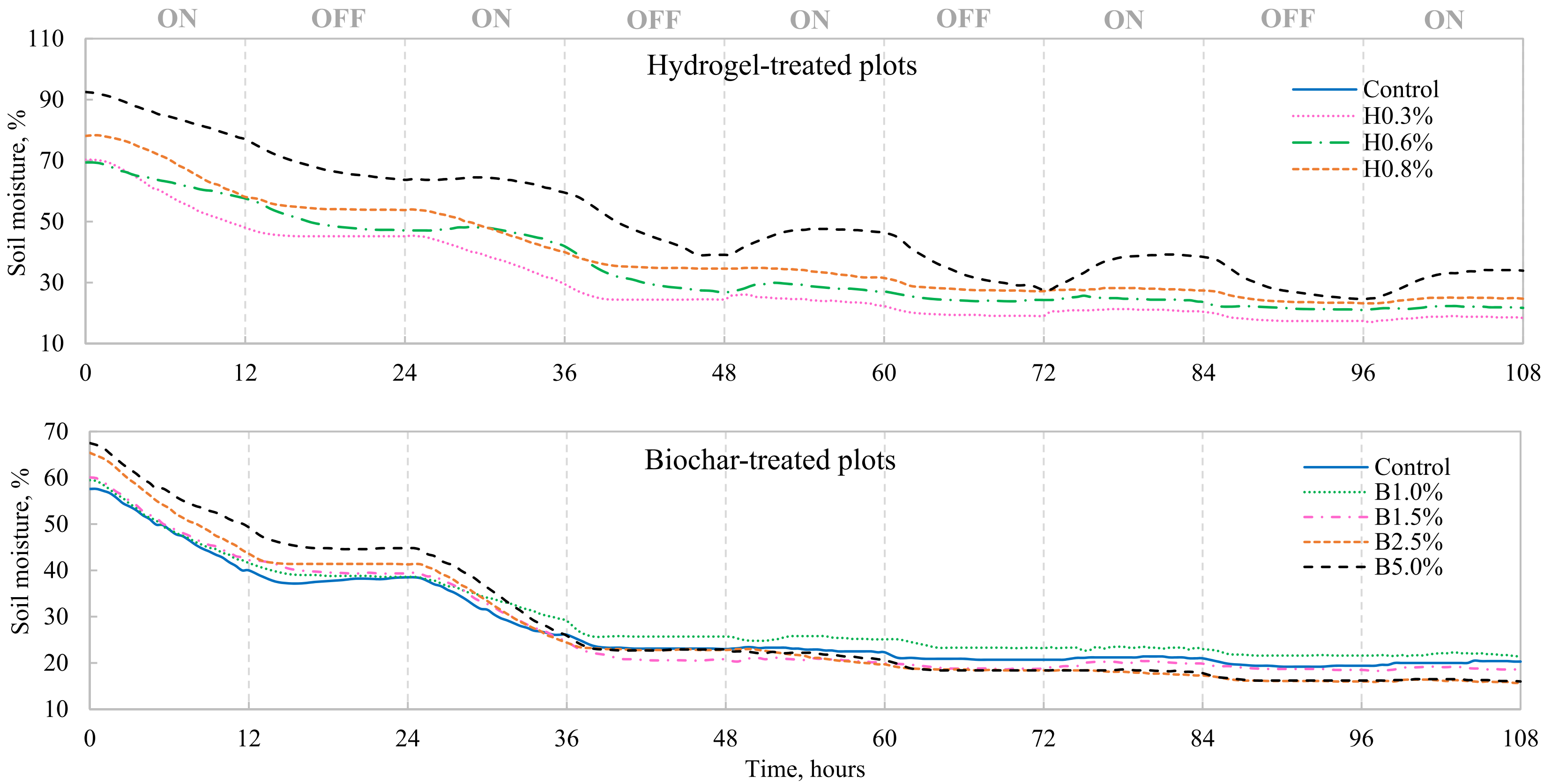


Figure 25. Variation in the water content in the substrates at 8-cm depth with time for hydrogel and biochar-treated plots.

It can be observed that the soil moisture for all the experimental plots exhibited similar behavior. The decrease in the moisture content at both the depths during the first two days proceeded relatively quickly, and then gradually slowed down until the end of the experimental period.

In the majority of the plots, a downward trend in the vapor migration was observed in the first few hours after the lamps were turned on (Figure 25). It was especially visible in the case of hydrogel-treated plots. At the beginning of the day, when the lamps were turned on, the vertical temperature gradient (between the surface and the bottom of the plot) caused a downward moisture movement, whereby water vapor from regions of higher temperature, i.e., the surface, was transported to areas of lower temperature, i.e., the bottom. An opposite effect was observed during the night time (Figure 24), wherein the water content at the depth of 3 cm increased due to the upward vapor migration from the warmer bottom to the colder surface.

In the case of hydrogel-treated plots, water content at the bottom and top layer of the samples was higher compare to the control plot. This trend maintained throughout the entire experimental period. Additionally, soil moisture increased significantly with an increase in polymer concentration. The highest values were obtained by plots with the highest hydrogel dosage, therefore H1.0% and H0.8%, respectively. However, it is worth mentioning that even the smallest amount of polymer amendment in the growing substrate significantly increased its water holding capacity. Consequently, more available water in the polymer-treated substrates led to more intensive evaporation and higher cooling effect.

In the case of plots with the biochar amendment, plots maintained higher water content in comparison with the control plot only during the first two to three days of the experiment. After that, achieved water contents were comparable with the control plot. Interestingly, during the last days of the experiment, plots with the highest biochar dosage expressed noticeably lower soil moisture values than the control plot. This observation is coherent with Bowen ratio analysis and supports the hypothesis that the addition of biochar, especially in higher concentrations, may lead to accelerated drying of the substrate. It might be caused by a relatively low specific surface area and total pore volume of used rice husk biochar.

4.4.2. Water retention structures

Figure 26 presents the variations in the substrate surface temperatures throughout the experiment. During the first and second day surface temperatures of all experimental plots were comparable and oscillated between approximately 60 and 65 ^oC. The surface temperature reduction occurred since the third day. Compare to the control plot, all the plots with water retention structures maintained lower temperatures. The most significant reduction appeared in the case of a sample with the retention plate and sample with the retention plate combined with the hydrogel amendment in the growing substrate. The temperature difference between mention samples and the control plot was 18 ^oC and 15 ^oC during the third day, 17 ^oC and 15 ^oC during the fourth day, and 6 ^oC and 5 ^oC during the fifth day, for retention plate sample and retention plate with hydrogel sample, respectively. The lowest surface temperature reduction occurred in the case of a plot with a granular layer, with a 10 ºC reduction during the third day, 5 ºC reduction during the fourth day, and 3 ºC reduction during the last day of the experiment.

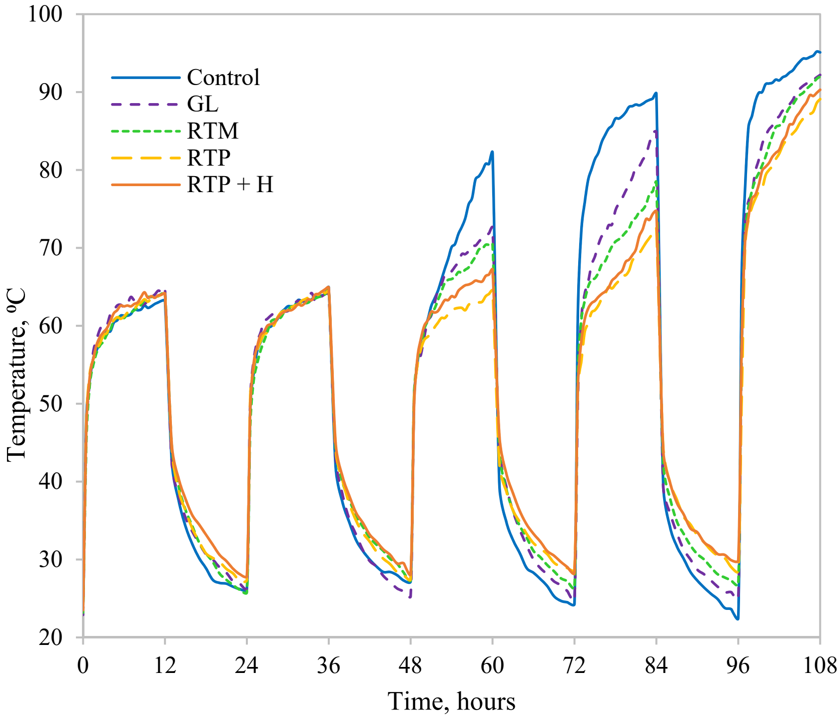
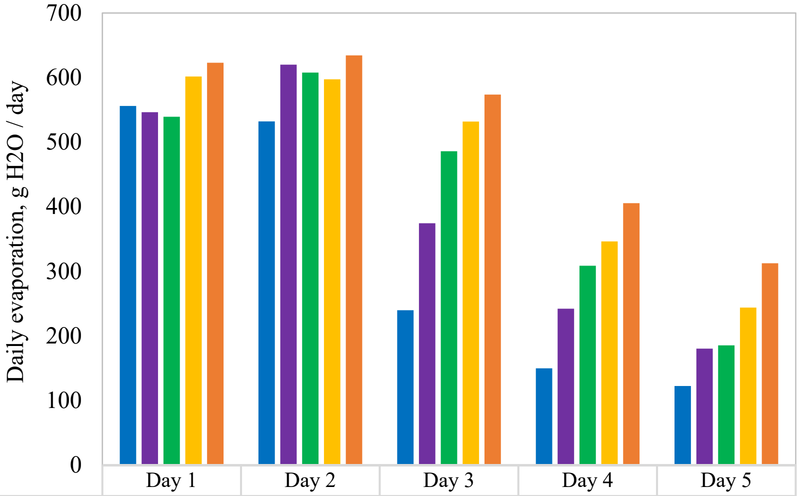


Figure 26. Variations of the substrate surface temperatures with time depending on the water retention structure used.

Plots equipped with retention plates noted also the highest surface temperatures during the night time. This phenomenon suggests the influence of the thermal inertia effect. Retention plate was a structure with the highest water storage capacity, therefore water volume and its high heat capacity very likely slowed down the rate at which the sample cooled down and heated up. Other retention structure samples expressed similar patterns, however, it was not as makeable.

Daily and cumulative evaporation are shown in Figure 27 and Figure 28, respectively. Plots with water retention structures achieved noticeably higher evaporation rates and evaporated in total significantly more water than plot without additional water retention.



	Day 1	Day 2	Day 3	Day 4	Day 5
Control	556	532	240	150	122
GL	546.4	620.0	374.4	242.1	180.4
RTM	539.3	607.7	485.9	308.6	185.4
RTP	601.7	597.2	531.8	346.4	243.9
RTP + H	623.0	634.3	573.6	405.5	312.6

Figure 27. Daily evaporation depending on the water retention structure used.

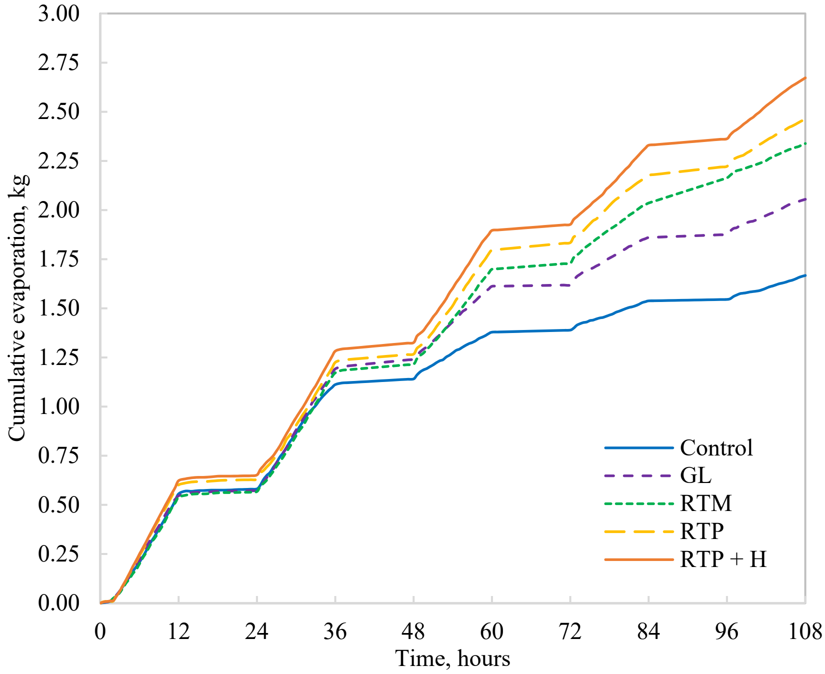


Figure 28. Cumulative evaporation depending on the water retention structure used.

During the first day of the experiment, therefore when all examined samples were relatively wet, the evaporation occurred at relatively similar rates. Through the second day, it could be seen that plots with water retention structures turned into water vapor more water compared to the control plot, however, the distinct difference started to be visible from the third day, where the evaporation rate of control plot was dramatically lower than other plots. In the case of samples with retention mat, retention plate, and retention plate combined with hydrogel, the evaporation rates achieved during the third and fourth days were over two times higher compared to the plot with no additional retention structure. The retention plate sample and combined retention plate and hydrogel plot maintained that significant difference till the end of the experiment.

Cumulative evaporation analysis (Figure 28) showed that application of water retention structures greatly increased the amount of total evaporated water, with a growth of 0.39 kg H_2O in case of the granular layer, 0.67 kg H_2O for a case of retention mat, 0.8 kg H_2O in case of the retention plate and 1.0 kg H_2O for retention plate combined with the addition of hydrogel to the substrate. This significant rise in the amount of evaporated water is associated with a great increase in the amount of released latent heat, therefore a reduction of sensible heat release and surface temperature reduction.

The time duration when latent heat flux dominated over sensible heat flux is illustrated in Figure 29. In comparison with the control plot, the application of water retention structures clearly intensified the latent heat release.

The time prolongation of latent heat dominance was shown by all the retention-equipped samples, with the longest prolongation time achieved by retention plate and retention plate with hydrogel in the substrate. Both samples expressed significant over 30 h prolongation, therefore latent heat was dominant there almost throughout the entire experiment, which remarkably reduced sensible heat flux and surface temperature.

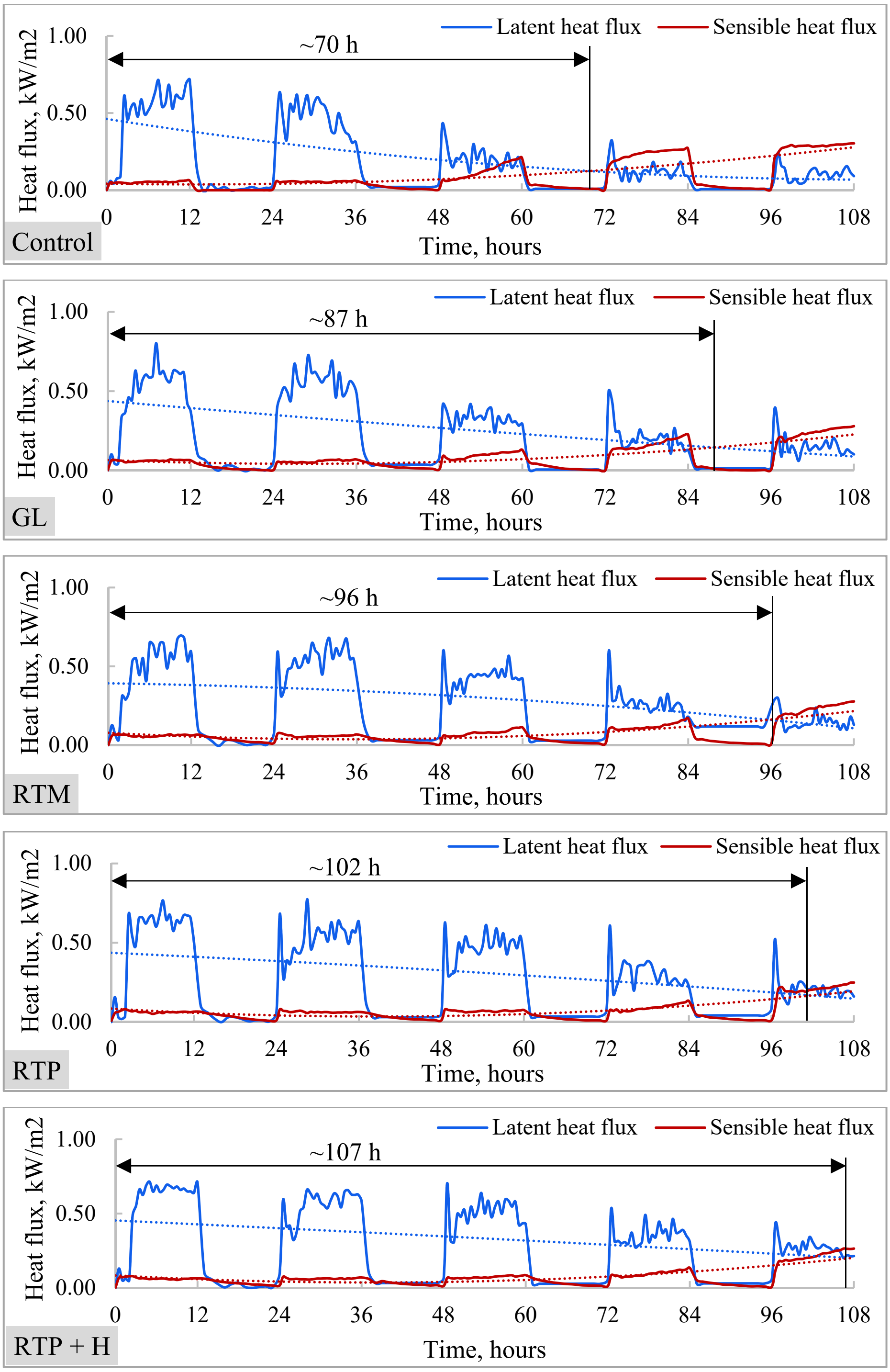
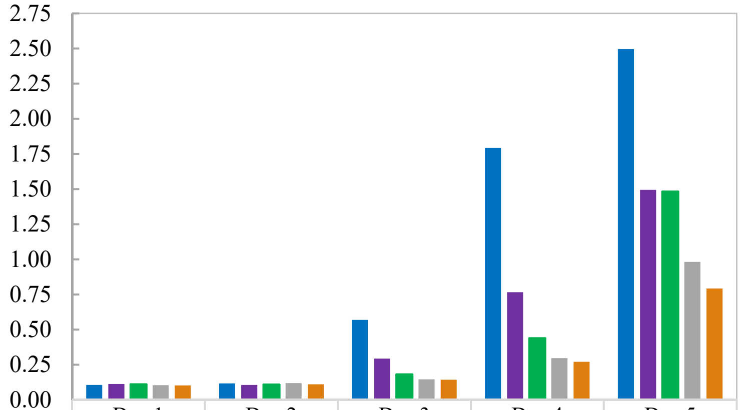


Figure 29. Variations in the latent and sensible heat fluxes, and the time of latent heat flux domination depending on the water retention structure used.

Plot with granular layer achieved the shortest prolongation time among all water retention structures, with 17 h longer latent heat domination. However, this result is still relatively high if we compare it to the plots examined in the experiment with soil amendments. The addition of the granular layer to the plot structure increased latent heat release similar to the application of the highest evaluated hydrogel concentrations in the substrate. It suggests that incorporation of water retention structures is a crucial solution to maximize the evaporation effect.

Daily average Bowen ratios calculated for all experimental plots are illustrated in Figure 30. It was observed, that similarly to the previous experiment, Bowen ratios stayed below value 1.0 during the first two days of the experimental period, due to relatively wet soil conditions and intensive evaporation. However, since the third day, there was a remarkable reduction in the case of samples with water retention structures. All these plots recorded two to three-fold lower Bowen ratios. This difference was even more spectacular during the fourth day of the experiment, with 57% Bowen ratio reduction in granular layer plot, 75% reduction in retention mat plot, 83% reduction in retention plate plot and 85% reduction in a plot with combined retention plate and hydrogel in the growing substrate.

Those significant reductions illustrate that water retention structures have a great impact on the amount of released latent heat and are important components that should be considered during the green roof design stage. Retention plate-equipped samples achieved the lowest Bowen ratios and maintained values lower than 1.0 throughout the entire experimental period, which again proves that this structure has the biggest potential to maximize green roof contribution in sensible heat reduction.



	Day 1	Day 2	Day 3	Day 4	Day 5
Control	0.11	0.12	0.57	1.79	2.50
GL	0.11	0.11	0.29	0.77	1.49
RTM	0.11	0.11	0.18	0.44	1.48
RTP	0.10	0.12	0.15	0.30	0.98
RTP + H	0.10	0.11	0.14	0.27	0.79

Figure 30. Average daily Bowen ratio depending on the water retention structure used.

Variations of the substrate water content were recorded only at 8 cm depth (bottom part of the plot) and are presented in Figure 31. Monitoring of soil moisture has shown that the application of water retention structures has an impact on soil water content. In the case of the granular layer and retention mat, it can be seen that in comparison to the control plot, the initial water content did not improve, however, used structures greatly slowed down the process of moisture dissipation within a sample, which was visible especially during first three days of the experiment.

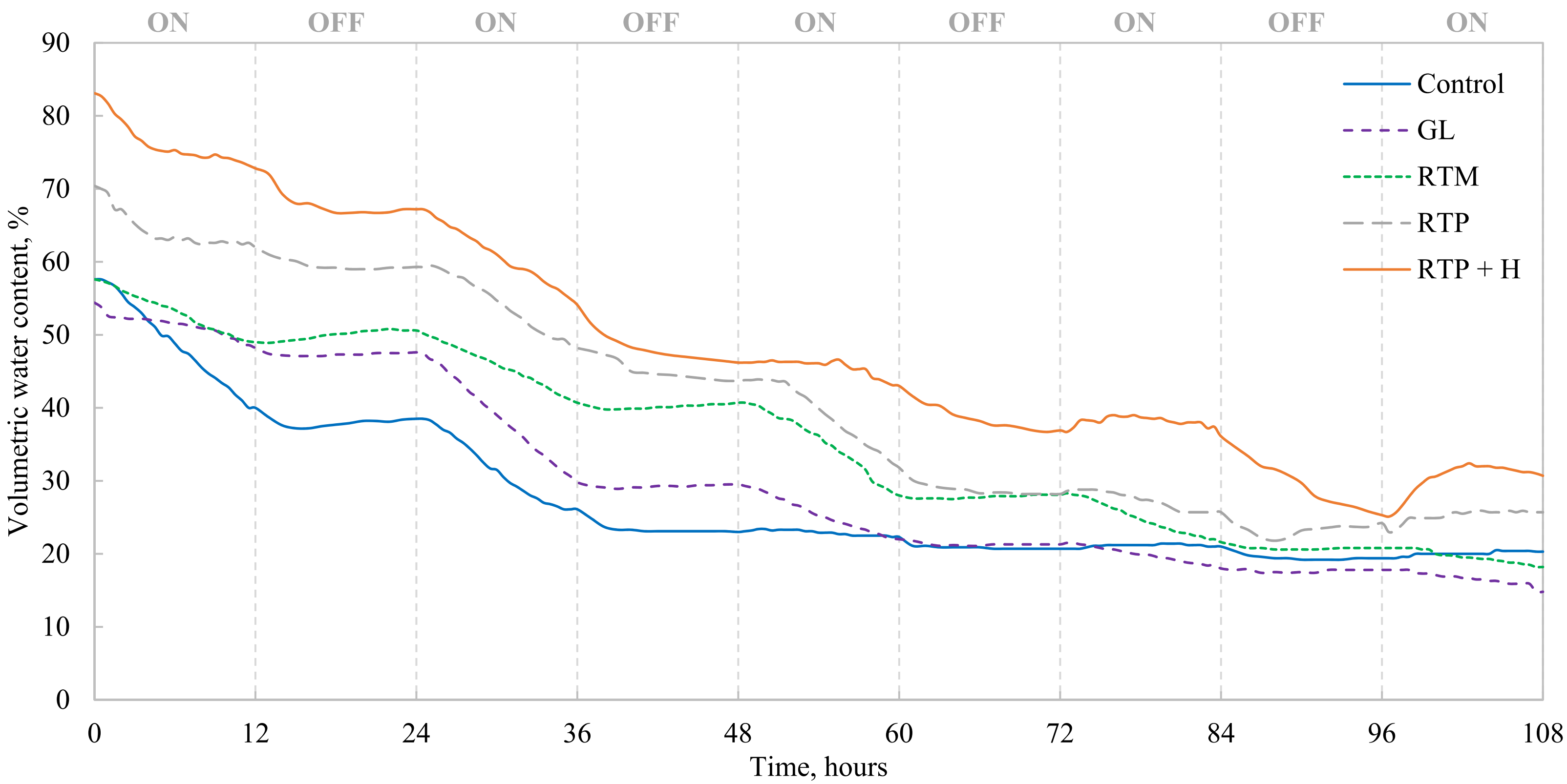


Figure 31. Variation in the water content in the substrates at 8-cm depth depending on the water retention structure used.

In the case of a plot with retention plate (RTP) and plot with retention plate combined with hydrogel in the substrate (RTP + H), the initial soil moisture expressed a significant increase, moreover water content stayed relatively high throughout the entire experiment. Retention plate with hydrogel additive in the substrate maintained the highest volumetric water content, which suggests that the combination of retention structure with soil amendment can be a good solution to improve green roof storage capacity and to provide more water available to evaporation.

All water retention structure-equipped plots proved that incorporation of water retention can not only increase the water holding capacity of the system but can also slow down the drying speed of the substrate and effectively contribute toward optimization of evaporation process and maximization of the release of latent heat. The water retention structure as a green roof component has a big impact on its thermal performance and can be effectively optimized.

Among examined structures, the waffle-shaped water retention plate displayed the highest potential to increase the system's water retention and can contribute the most effectively toward sensible heat flux reduction. This potential can be also further expanded by the inclusion of soil amendments in the growing substrate.

Chapter 5. Design recommendations to optimize the evaporation and latent heat release at green roofs

The green roof design should be developed and adapted to suit not only the purpose of improving the building's interior and its energy efficiency but also the outdoor conditions. Initial design considerations are vital to constructing a system that fulfills both those purposes. The results of the conducted experiments clearly showed that the green roof design can be effectively optimized.

Figure 32 shows the growing substrate temperature reduction that can be achieved by amending the soil with super absorbent polymer and inclusion of water retention structure in comparison to bare soil. An increase in the cumulative evaporation (Figure 33) and a significant reduction in the Bowen ratio (Figure 34) also demonstrate that latent heat release can be greatly increased by simple incorporation of hydrogel and/or water retention in the system. The difference between the performance of bare soil itself and soil supported by water-absorbent amendment and water storage structure in different configurations presents the great potential of cooling effect improvement in both indoor and outdoor environments. The surface temperature reduction and improved evaporation will result not only in sensible heat flux decrease but also in a great cutback of the building's cooling loads and energy consumption.

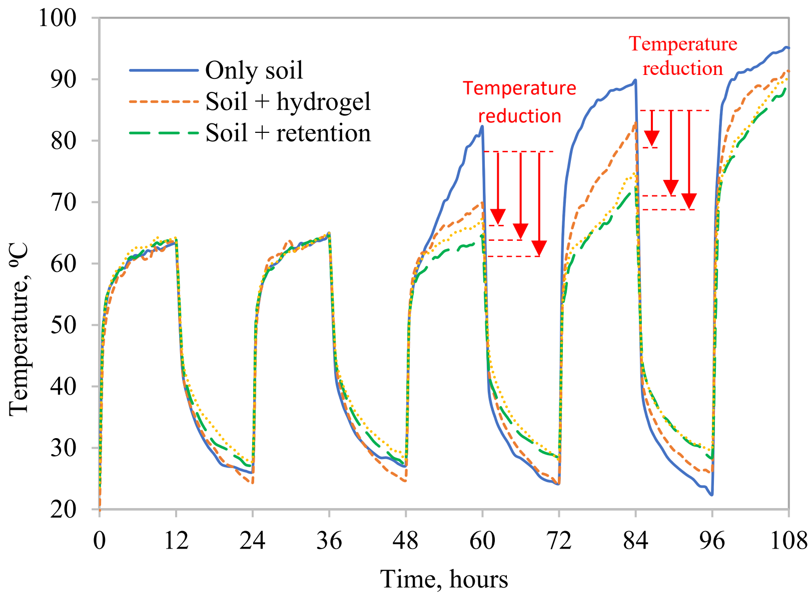


Figure 32. Potential surface temperature reduction due to system optimization.

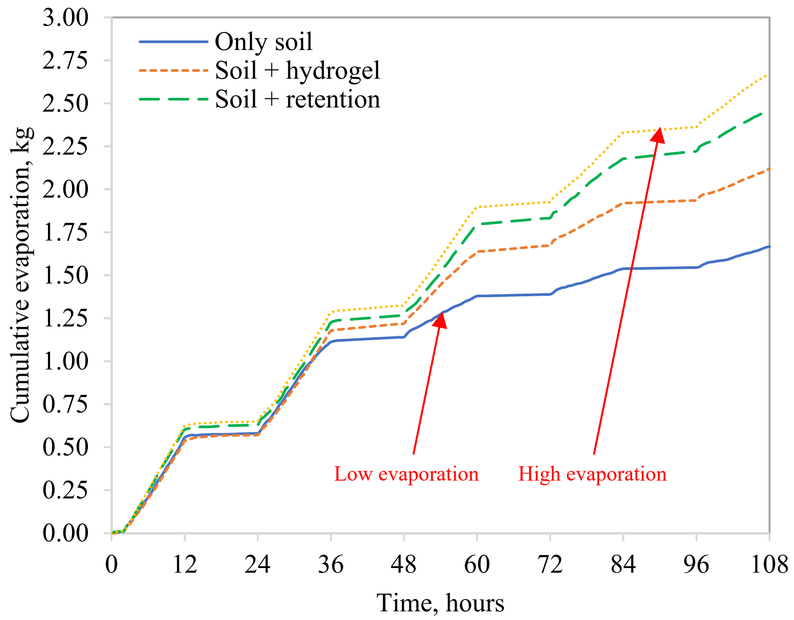


Figure 33. Potential cumulative evaporation increase due to green roof system optimization.

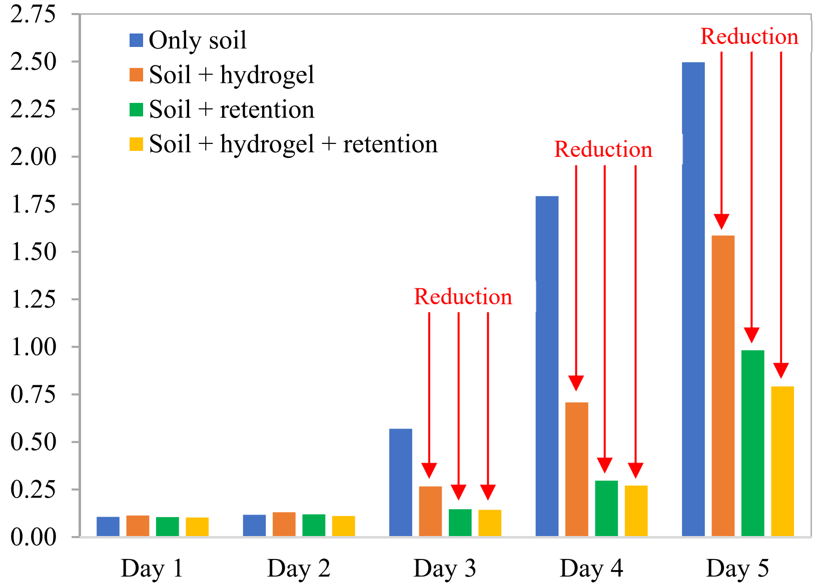


Figure 34. The potential to reduce the Bowen ratio by optimizing the green roof system.

Evaluation of the application of soil amendments to the green roof growing substrates revealed that hydrogel is an additive with great potential toward the increase of evaporation and latent heat release combined with green roof water storage capacity expansion. The energy performance of soil amended with hydrogel was remarkably better compared to the non-amended substrate. Hence, incorporation of the superabsorbent polymer in the green roof growing substrate is recommended for indoor and outdoor environment improvement. Furthermore, the inclusion of hydrogel might be also advantageous for urban flood control and beneficial for rooftop vegetation assembly. Due to its water storage ability, it can potentially provide higher amounts of water available for plant transpiration processes, therefore the cooling potential can possibly be greater than investigated. Nevertheless, further studies focused on the impact of hydrogel on the green roof's plant community are required.

Among evaluated polymer concentrations, it was clear that increase of hydrogel concentration in the substrate has a positive influence on the overall energy performance of the plot, however, it is important to notice that the highest investigated concentrations (0.8% and 1.0% w/w) achieved very similar results in terms of evaporation and latent heat release. Thus, the study suggests that a further increase in concentration may not result in a corresponding improvement in the evaporation and latent heat transfer behaviors. Moreover, it can be potentially disadvantageous for the plants due to the possibility of root wilting. Hence, the study suggests the recommended hydrogel concentration for green roof growing substrate between 0.6% and 0.8% w/w.

On the other hand, the application of rice husk biochar was counterproductive. It decreased the overall energy performance and speeded up the soil drying process, therefore despite the numerous advantages of rice husk biochar as a soil amendment, it is not recommended additive for green roof use due to its disadvantageous influence on the system energy performance. The study suggests that the application of rice husk biochar, especially in higher concentrations, might lead to not only increasing surface temperature and excessive release of sensible heat into the atmosphere but also can affect the building indoor environment and contribute to the increase of cooling loads and building's energy consumption.

Experimental results of the study focused on the influence of water retention structures on the green roof energy balance showed that water retention structures are the most vital components toward evaporation, latent heat release, and water storage enhancement. All evaluated structures had the biggest impact on energy performance improvement. The choice of the most suitable structure should be based on the desired green roof purpose. However, study results suggest that the water retention plate is a structure that should be primarily considered during the designing process. It would not only the most effectively contribute toward stormwater control and urban flood mitigation, but also can bring the highest benefits from the energy performance point of view.

Finally, the combination of both water absorbent amendment and retention structure is another option that has great potential to optimize green roof performance. While hydrogel would ensure a straight increase of soil field capacity and amount of water available for evaporation, the retention structure would provide the storage of the excess water, increasing the system water holding capacity and water utilization, since accumulated water can be transported back to the soil during drought period. Hence, incorporation of both solutions together has the highest potential to intensify the evaporation and latent heat release and at the same time provide a notable surface temperature reduction and stormwater mitigation.

In this fact, growing substrate and water retention structures are components that are substantial for the green roof energy performance, therefore should be carefully considered during the system design stage. The choice of proper components will result in long-term benefits for both the building and the environment.

Chapter 6. Conclusions

In this study, two different soil amendments to the green roof substrate (hydrogel and rice husk biochar), as well as three different water retention structures (granular layer, retention mat and retention plate) were tested in form of differently composed plots to investigate their influence on the evaporation and latent heat transfer behaviors. The results showed that both soil amendments and water retention structures increased the substrate's water storing capacity and had a significant influence on the evaporation and the amount of released latent heat. The water content in the substrate had an effect on the evaporation and duration of its cooling effect. The plots with higher water content showed more intense evaporation with longer periods of time. The water stored in the substrate also relatively reduced its surface temperature, which in turn, did not only decrease the amount of sensible heat released into the atmosphere but also reduced the cooling loads of the building, thus contributing to curtailing its energy demand. Increased water holding capacity can contribute to stormwater runoff reduction, the stored water can be also useful for green roof vegetation.

Results show that rice husk biochar improved the initial water holding capacity of the soil and increased evaporation and latent heat release, however, this improvement occurred only during the first two to three days of experiment and was not significant. Moreover increasing the biochar concentration led to accelerating drying of the soil and higher surface temperatures at the end of the experiment, therefore contributed in the increase of sensible heat release.

The data from the experiment demonstrated that aiming for the evaporation and latent heat release improvement, the hydrogel is more suitable additive than biochar. Hydrogel significantly improved evaporation and reduced surface temperature. It also noticeably decreased the Bowen ratio by effectively contributing to latent heat release and therefore reduction of sensible heat flux. Even small amounts of the polymer in the growing substrate significantly increased the substrate's water holding capacity and improved its evaporation behavior. The increase in the hydrogel concentration can raise the amount of stored water and consequently increase the cumulative evaporation; however, there is no significant difference between the results from the two plots with the highest polymer concentration (H0.8% and H1.0%). Hence further increase in concentration may not result in comparable improvement in the evaporation and latent heat release.

The study demonstrated that the inclusion of water retention structures is crucial to achieving optimal evaporation effects. Incorporation of retention structures did not only remarkably enhanced the latent heat release and sensible heat reduction but also greatly increased system water storage capacity, which is an important factor for urban flooding control, system drought stress resistance, and cooling potential improvement. Water retention plate is a structure that due to its outstanding benefits in both energy performance and water storage capacity is the most recommended to include in the green roof design.

The findings from this study might be a base for new policy suggestions, such as law enforcement of green roof applications or financial incentives for the large establishments investing in green infrastructure, aiming the reduction of surface impermeability in the urban areas. Last but not least, the research highlights that the green roof could be optimized to enhance the evaporation behavior and latent heat transfer towards urban environment improvement, therefore can support the campaigns targeting the social awareness about and the urban heat island phenomena, its consequences and possible solutions for its mitigation.

Nevertheless, further research should be conducted to evaluate the effect of investigated components in combination with vegetation growth. Above all, it is crucial to examine the influence of hydrogel-amended soils on the green roof plant community and what polymer concentration would be optimal to maximize the amount of plant's available water and at the same time prevent root wilting. It would be also favorable to investigate suggested optimization options in a real scale green roof system. Such studies would ultimately complement this research and promote an effective development in the energy efficiency of the green roofs.

References

Abedi-Koupai, J., et al. (2008). "Evaluation of Hydrogel Application on Soil Water Retention Characteristics." Journal of Plant Nutrition **31**(2): 317-331.

ASHRE (2017). 2017 Ashrae Handbook. Chapter 4: Heat Transfer.

Ayata, T., et al. (2011). "An Investigation of Sensible Heat Fluxes at a Green Roof in a Laboratory Setup." Building and Environment **46**(9): 1851-1861.

Baik, J.-J., et al. (2012). "Effects of Building Roof Greening on Air Quality in Street Canyons." Atmospheric Environment **61**: 48-55.

Barrio, E. P. D. (1998). "Analysis of the Green Roofs Cooling Potential in Buildings." Energy and Buildings **27**(2): 179-193.

Beck, D. A., et al. (2011). "Amending Greenroof Soil with Biochar to Affect Runoff Water Quantity and Quality." Environmental Pollution **159**(8): 2111-2118.

Bevilacqua, P., et al. (2016). "Experimental Investigation of the Thermal Performances of an Extensive Green Roof in the Mediterranean Area." Energy and Buildings **122**: 63-79.

Bruun, E. W., et al. (2014). "Biochar Amendment to Coarse Sandy Subsoil Improves Root Growth and Increases Water Retention." Soil Use and Management **30**(1): 109-118.

Cascone, S. (2019). "Green Roof Design: State of the Art on Technology and Materials." Sustainability **11**: 3020.

Chen, S., et al. (2015). "Urbanization Effect on Precipitation over the Pearl River Delta Based on Cmorph Data." Advances in Climate Change Research **6**.

Chow, M. F. and M. F. Abu Bakar (2018). Environmental Benefits of Green Roof to the Sustainable Urban Development: A Review.

Christen, A. and R. Vogt (2004). "Energy and Radiation Balance of a Central European City." International Journal of Climatology **24**(11): 1395-1421.

Chung, J. (2019). Infiltration and Evaporation Behavior of Infiltration Facilities According to the Characteristic of Filling Material. Department of Civil and Environmental Engineering. Seoul National University, Seoul National University. **Master's Thesis**.

Coutts, A. M., et al. (2007). "Impact of Increasing Urban Density on Local Climate: Spatial and Temporal Variations in the Surface Energy Balance in Melbourne, Australia." Journal of Applied Meteorology and Climatology **46**(4): 477-493.

Djedjig, R., et al. (2012). "Development and Validation of a Coupled Heat and Mass Transfer Model for Green Roofs." International Communications in Heat and Mass Transfer **39**: 752-761.

Farrell, C., et al. (2013). "Water-Retention Additives Increase Plant Available Water in Green Roof Substrates." Ecological Engineering **52**: 112-118.

Feng, C., et al. (2010). "Theoretical and Experimental Analysis of the Energy Balance of Extensive Green Roofs." Energy and Buildings **42**(6): 959-965.

Gartland, L. M. (2008). Heat Islands. Understanding and Mitigating Heat in Urban Areas. London, Routledge**:** 208.

Getter, K. and D. Rowe (2006). "The Role of Extensive Green Roofs in Sustainable Development." HortScience: a publication of the American Society for Horticultural Science **41**: 1276.

Glaser, B., et al. (2002). "Ameliorating Physical and Chemical Properties of Highly Weathered Soils in the Tropics with Charcoal – a Review." Biology and Fertility of Soils **35**(4): 219-230.

Grimmond, C. S. B., et al. (2004). "Flux and Turbulence Measurements at a Densely Built-up Site in Marseille: Heat, Mass (Water and Carbon Dioxide), and Momentum." Journal of Geophysical Research: Atmospheres **109**(D24).

Harper, G. E., et al. (2015). "Nine-Month Evaluation of Runoff Quality and Quantity from an Experiential Green Roof in Missouri, USA." Ecological Engineering **78**: 127-133.

Huang, P., et al. (2011). Handbook of Soil Sciences: Properties and Processes, Second Edition.

Jaffal, I., et al. (2012). "A Comprehensive Study of the Impact of Green Roofs on Building Energy Performance." Renewable Energy **43**: 157-164.

Johnson, M. S. (1984). "Effect of Soluble Salts on Water Absorption by Gel-Forming Soil Conditioners." Journal of the Science of Food and Agriculture **35**(10): 1063-1066.

Karasu, B., et al. (2007). Lightweight Expanded Aggregate Production from Bottom Ash.

Kravčík, M., et al. (2008). "Water for the Recovery of the Climate - a New Water Paradigm." Retrieved 2019.12.20.

Kumar, R. and S. C. Kaushik (2005). "Performance Evaluation of Green Roof and Shading for Thermal Protection of Buildings." Building and Environment **40**(11): 1505-1511.

La Roche, P. and U. Berardi (2014). "Comfort and Energy Savings with Active Green Roofs." Energy and Buildings **82**: 492-504.

Lazzarin, R. M., et al. (2005). "Experimental Measurements and Numerical Modelling of a Green Roof." Energy and Buildings **37**(12): 1260-1267.

Lee, J. Y., et al. (2013). "Quantitative Analysis on the Urban Flood Mitigation Effect by the Extensive Green Roof System." Environmental pollution (Barking, Essex : 1987) **181C**: 257-261.

Lundholm, J. (2015). "Green Roof Plant Species Diversity Improves Ecosystem Multifunctionality." Journal of Applied Ecology **52**.

MacIvor, J. S. and J. Lundholm (2011). "Insect Species Composition and Diversity on Intensive Green Roofs and Adjacent Level-Ground Habitats." Urban Ecosystems **14**: 225-241.

Madre, F., et al. (2014). "Green Roofs as Habitats for Wild Plant Species in Urban Landscapes: First Insights from a Large-Scale Sampling." Landscape and Urban Planning **122**: 100-107.

Major, J., et al. (2010). "Major J, Rondon M, Molina D, Riha Sj, Lehmann J.. Maize Yield and Nutrition During 4 Years after Biochar Application to a Colombian Savanna Oxisol. Plant Soil 333: 117-128." Plant and Soil **333**: 117-128.

Marin, M., et al. (2014). "Green Roofs for a Drier World: Effects of Hydrogel Amendment on Substrate and Plant Water Status." Science of The Total Environment **490**: 467–476.

Miao, S., et al. (2012). "Analysis of Observations on the Urban Surface Energy Balance in Beijing." Science China Earth Sciences **55**(11): 1881-1890.

Montesano, F. F., et al. (2015). "Biodegradable Superabsorbent Hydrogel Increaseswater Retention Properties of Growing Media and Plant Growth." Agriculture and Agricultural Science Procedia **4**: 451-458.

Mulcahy, D. N., et al. (2013). "Biochar Soil Amendment Increases Tomato Seedling Resistance to Drought in Sandy Soils." Journal of Arid Environments **88**: 222–225.

Onmura, S., et al. (2001). "Study on Evaporative Cooling Effect of Roof Lawn Gardens." Energy and Buildings **33**(7): 653-666.

Parizotto, S. and R. Lamberts (2011). "Investigation of Green Roof Thermal Performance in Temperate Climate: A Case Study of an Experimental Building in Florianópolis City, Southern Brazil." Energy and Buildings **43**(7): 1712-1722.

Peng, L. L. H., et al. (2019). "Thermal and Energy Performance of Two Distinct Green Roofs: Temporal Pattern and Underlying Factors in a Subtropical Climate." Energy and Buildings **185**: 247-258.

Pugh, T., et al. (2012). "Effectiveness of Green Infrastructure for Improvement of Air Quality in Urban Street Canyons." Environmental science & technology **46**: 7692-7699.

Rakhshandehroo, M., et al. (2015). "Mitigating Urban Heat Island through Green Roofs." Current World Environment **10**.

Sailor, D. J., et al. (2008). "Thermal Property Measurements for Ecoroof Soils Common in the Western U.S." Energy and Buildings **40**(7): 1246-1251.

Simmons, M. T., et al. (2008). "Green Roofs Are Not Created Equal: The Hydrologic and Thermal Performance of Six Different Extensive Green Roofs and Reflective and Non-Reflective Roofs in a Sub-Tropical Climate." Urban Ecosystems **11**(4): 339-348.

Tabares-Velasco, P. C. and J. Srebric (2011). "Experimental Quantification of Heat and Mass Transfer Process through Vegetated Roof Samples in a

New Laboratory Setup." International Journal of Heat and Mass Transfer **54**: 5149-5162.

Takakura, T., et al. (2000). "Cooling Effect of Greenery Cover over a Building." Energy and Buildings **31**(1): 1-6.

Tan, C. L., et al. (2017). "Impact of Soil and Water Retention Characteristics on Green Roof Thermal Performance." Energy and Buildings **152**: 830-842.

Theodosiou, T. G. (2003). "Summer Period Analysis of the Performance of a Planted Roof as a Passive Cooling Technique." Energy and Buildings **35**(9): 909-917.

Townshend, D. and A. Duggie (2007). "Study on Green Roof Application in Hong Kong."

Vijayaraghavan, K., et al. (2012). "A Field Study to Evaluate Runoff Quality from Green Roofs." Water Research **46**(4): 1337-1345.

Wong, N. H. and Y. Chen (2008). "Tropical Urban Heat Islands: Climate, Buildings and Greenery." Tropical Urban Heat Islands: Climate, Buildings and Greenery: 1-259.

Wong, N. H., et al. (2003). "Investigation of Thermal Benefits of Rooftop Garden in the Tropical Environment." Building and Environment **38**(2): 261-270.

Zhang, Q., et al. (2015). "The Capacity of Greening Roof to Reduce Stormwater Runoff and Pollution." Landscape and Urban Planning **144**: 142-150.

Zhenyu, W., et al. (2013). "Impacts of Adding Biochar on Nitrogen Retention and Bioavailability in Agricultural Soil." Geoderma **206**: 32–39.

국문초록

옥상녹화의 구성요소가 증발 및 잠열 전달에 미치는 영향

말비나 수차네카

건설환경공학부

서울대학교 공과대학

급격한 도시화와 도시지역의 확장으로 지반의 투수성이 저하되고 지표면 온도가 상승하여 도시 열섬현상이 발생하게 되었다. 최근 몇 년간 옥상 녹화는 열섬현상 완화를 위한 잠재적 전략으로 점점 더 많은 관심을 끌고 있다. 그러나 이전의 연구에서는 옥상 녹화의 증발이 대기 중으로 방출되는 잠열의 양에 미치는 영향을 고려하지 않았다. 이에 본 연구는 두 가지 옥상녹화 구성요소 (옥상녹화 증발과 잠열 전달의 영향 측면에서 기질 및 저류 구조)를 평가하고, 현열 유속 감소를 위한 옥상녹화 설계 권고안을 제안하는 것을 목적으로 한다.

2 개의 서로 다른 토양 개량제 (초흡수성 중합체 및 왕겨 바이오차)로 처리된 옥상녹화 기질과 3 개의 저류 구조물(알갱이층, 저류 매트, 저류판)의 구성들, 토양 개량제와 저류 구조를 모두 결합한 구성을 5 일간 특별하게 설계된 증발기에서 실험하였다. 기질 표면 온도, 일일 및 누적 증발, 잠열 및 현열 플럭스, 보웬 비율 및 체적 함수비가 비교되었다.

실험 결과는 기질에 첨가제를 추가하면 물 보유 용량이 크게 증가함을 보여주었다. 또한, 수분 함량의 증가는 누적 증발량을 증가시켜 냉각 효과를 일으켰다. 물 보유량이 증가함에 따라 표면온도가 감소하고, 잠열 플럭스가 현열 플럭스보다 우세한 시간을 연장하였다. 이 연구는 왕겨 바이오차 적용이 옥상 녹화 에너지 성능에 유리하지 않다고 보여준다. 토양 내 바이오차 농도의 증가는 플롯의 건조율을 가속화 시키고, 수분 함량을 빠르게 고갈시켰으며 기질 표면 온도 상승으로 현열 전달이 더 많이 이루어졌다. 따라서, 잠열 방출 개선을 다루면서, 이 연구는 하이드로젤 개조가 옥상 녹화 에너지 성능을 최대화하기 위해 선호적으로 고려될 수 있음을 시사한다.

저류 구조의 효과에 관한 조사는 증발, 잠열 방출, 물 보유량 증대를 위한 가장 중요한 옥상녹화 구성 요소라는 것을 보여주었다. 유지 구조를 적용하면 증발이 현저히 증가하였고, 따라서 잠열 방출과 기질 표면 온도는 현저하게 감소하였다. 평가된 구조물 중에서, 저류판은 효과적인 물 보유와 증발 향상에 기여할 수 있는 가장 높은 잠재력을 보였다. 저류판이 부착된 플롯의 경우, 잠열은 거의 전체 실험에서 우세한 열 플럭스로 작용했으며, 이에 따라 가장 높은 냉각 효과를 제공하였다. 더욱이, 이 연구는 초흡수성 중합체와 저류 구조를 함께 결합하면 증발 효과를 높이고 상당한 표면 온도를 감소시킬 수 있는 가장 높은 잠재력을 가지고 있음을 시사한다.

본 연구의 결과는 시스템으로서 옥상 녹화가 열 환경 개선을 최적화할 수 있다는 것을 확인시켜 주었다. 기질과 저류 구조는 모두 옥상녹화 에너지 성능에 필수적인 구성 요소이므로 설계 과정에서 철저하게 고려되어야 한다. 이처럼 적절한 구성요소를 선택하면 건물과 환경 모두에게 장기적인 이익을 가져다 줄 것이다.

키워드: 바이오차; 증발; 옥상녹화; 잠열; 초흡수성 중합체; 저류 구조; 도심 열섬현상

학번: 2018-20151

학위논문 초본

최근 몇 년간 도시 지역의 광범위한 발전은 식생이 건물과 포장된 표면으로 대체되는 등 경관에 심각한 변화를 초래하였다. 투수성 표면을 건조하고 비투수성 포장으로 교체하면 열 흡수가 증가하고 수분 침투, 저류, 증발 및 식물 증산작용을 감소시킨다. 증발과 증산작용에 이용되는 물의 양이 적으면 잠열이 적게 방출되고, 지표면 온도가 높아지며, 대기로 방출되는 열의 양이 많아진다. 이러한 변화들은 도시가 지방보다 따뜻해지는 주요 요인 중 하나이며, 도시 열섬(UHI) 현상을 초래한다.

UHI 는 인간의 건강, 대기질, 도시의 에너지 소비에 부정적인 영향을 미친다. 또한 도시화가 강수량에 영향을 미치는 것으로 보고되었는데, 도시들은 지방에 비해 강수빈도가 적고 짧은 것으로 나타났다. 도시의 기온 상승은 온열로 인한 불쾌감과 온열 질환의 위험을 높이는 것으로 대기 중으로 방출되는 현열 플럭스에 영향을 받는다. 예를 들어 아스팔트 도로나 콘크리트 지붕과 같이 불침투성 표면의 경우, 순방사선의 형태로 표면이 받는 에너지는 부분적으로 표면을 통해 멀리 전도된다. 그러나 물의 부족 또는 제한된 가용성으로 인해 입사 태양 에너지의 주요 부분은 현열로 변경된다. 물과 식물을 이용할 수 있는 투수성 포장의 경우, 태양 에너지의 상당 부분이 수증기를 통해 잠열로 소산될 수 있고, 소량만이 현열로 변환될 것이다.

불침투성 표면은 태양 에너지의 최대 60%를 지각 있는 열로 변환할 수 있는 반면, 물에 포화된 표면은 태양 복사의 최대 80%를 기화 현열로 변환할 수 있다. 따라서 광범위한 편익을 가진 지속가능한 건축기술로 인기를 얻고 있는 옥상 녹화와 같은 투수성 표면 포장은 현열 플럭스 저감을 위한 잠재적인 해결책이 될 수 있다. 지난 10 년간 옥상 녹화를 통한 열섬 현상 완화 전략은 다양한 연구 대상이 되었다.

옥상 녹화는 건물 구조물(대개 건물 옥상)의 토양 상태를 재현하는 표면이다. 그들은 도시의 광범위한 개발로 인한 표면 손실을 보상한다. 옥상 녹화의 개념과 도시 경관을 위한 미적·생태적 의미는 지속 가능한 발전이라는 개념과 일맥상통한다.

수많은 연구들은 옥상 녹화가 열섬현상 완화뿐만 아니라 대기 질과 수질 개선, 생물다양성 보존에 기여하고 폭풍우 유출을 감소시킨다는 것을 입증해왔다. 게다가, 옥상 녹화 시스템은 건물의 단열재에 영향을 미친다. 따라서 많은 연구자들이 실험실 규모와 현장 규모 연구 모두에서 옥상 녹화의 에너지 절약 가능성을 입증해왔다.

최근 연구에서는 토양 개량제를 사용하여 옥상 녹화 기질의 수분 보유 능력을 성공적으로 증가시킬 수 있다고 제안하고 있다. 농업에서 일반적으로 사용되는 가장 인기 있는 개량제 중 하나는 하이드로겔이라고도 알려진 초흡수성 고분자(SAP)이다. 하이드로겔은 조경, 농업, 원예, 임업 등에 사용되는 토양에 사용되고, 널리 이용될 수

있는 인공적인 저류 첨가제이다. 이것은 무게의 수백 배에 달하는 물을 흡수하고 저장하는 능력이 특징이다. 또 다른 유망한 첨가제는 바이오차다. 바이오차(biochar)는 천연 토양 개량제로서 많은 혜택을 받는 탄산화 바이오매스다. 연구에 따르면 바이오차는 물을 함유할 수 있어 잠재적으로 기질의 수분 보유 능력을 향상시킬 수 있으며 따라서 현열 감소에 기여할 수 있다.

본 연구는 열섬현상 완화에 기여하기 위해 현열 저감을 향한 옥상 녹화의 개선 가능성을 조사하였다. 이번 연구는 증발 및 잠열 전달을 높이기 위해 옥상 녹화 구성요소가 성공적으로 최적화될 수 있음을 증명할 것으로 기대된다. 구체적인 목적은 다음과 같다.

(1) 옥상 녹화의 열과 에너지 균형을 정량화하기 위한 리액터 설계를 제안한다.

(2) 성장하는 기질에 대한 수용성 첨가제의 효과와 증발 및 잠열 전달에 관한 옥상 녹화 저류 구조물의 적용을 평가한다.

(3) 현열 감소를 위해 증발 및 잠열 방출을 최적화하는 옥상 녹화 설계 권고안을 제안한다.

실험은 특수 설계된 증발 리액터에서 수행되었다. 리액터는 투명한 아크릴 원통형으로 구성되었고, 응축수 배수구로 응축수가 중력에 따라 흐를 수 있는 각도로 스탠드 위에 배치되었다. 원통형의 커버는

주변으로의 수분 손실을 방지하고 증발에 대한 바람의 영향을 없애기 위해 밀폐되었다.

실험 플롯은 아크릴 상자에 넣었다. 각각의 실험이 시작되기 전에 조사된 플롯이 있는 아크릴 박스는 미리 준비된 강우 시뮬레이션 사이트를 사용하여 60 mm/h 의 비율로 1 시간 가량 시뮬레이션 강우에 노출시켰다. 태양 복사는 실험 현장 위의 스탠드에 고정된 5 개의 UV-A 전구를 사용하여 시뮬레이션되었다. 이 램프는 낮과 밤의 상태를 시뮬레이션하기 위해 12 시간 간격으로 작동되었다.

복사열은 기질에 의해 흡수되고 토양 수분은 증발할 것이다. 그 결과 습한 공기의 밀도가 높아지고 투명한 덮개의 내부 표면에 습기가 응축될 것이다. 따라서 응축된 물은 중력에 의해 보조된 원통형 커버의 바닥을 향해 자연스럽게 흐른 다음, 커버의 아래쪽 끝에 있는 응축수 배수구에 의해 응축수 저장 용기로 방출된다. 리액터 내 용수와 응축수의 변화는 30 분 간격으로 두 개의 별도의 디지털 저울로 측정되었다. 열전대와 시간영역 반사계 토양 수분 센서를 리액터 내부에 배치해 기질 표면 온도, 리액터 내부의 공기 온도, 샘플 내 수분 함량을 측정하였다. 또한, 리액터 내부의 공기 습도는 습도계를 사용하여 측정하였다.

제안된 증발형 리액터는 제어된 환경에서 증발 조사와 에너지 분석에 필수적인 매개변수를 비교적 쉽게 측정할 수 있게 해준다.

에너지 분석에는 잠열유속과 현열유속, 이 두 가지 열 유속 계산과 그 결과로서 보웬비가 포함되었다. 건조 과정 동안 기질에서 증발할 수 있는 물의 양이 점차 감소하여 잠열 방출의 우세에서 강력한 현열 방출로 전환된다. 시간 경과에 따른 두 개의 열 유속을 계산하면 샘플 간의 증발 시간을 비교할 수 있으며, 현열이 잠열 방출을 초과하기 시작할 때, 즉 수동적인 냉각 효과가 감소하기 시작할 때를 알아낼 수 있다. 보웬비처럼 단순 인자의 형태로 두 플럭스를 연결함으로써 증발 효율과 잠열 방출의 측면에서 매우 쉽게 습윤 표면을 비교할 수 있다.

본 연구에서는 옥상 녹화 기질에 대한 2 개의 서로 다른 토양 개량제(하이드로겔 및 왕겨 바이오차) 뿐만 아니라 3 개의 서로 다른 저류 구조(분해층, 저류 매트 및 저류 판)를 서로 다르게 구성하여 증발 및 잠열 전달 거동에 미치는 영향을 조사하였다. 전체적으로, 평가된 실험 플롯은 다음과 같다. 대조구인 비처리 토양 표본 1 개, 0.3%, 0.6%, 0.8%, 1.0% w/w 농도의 폴리머와 하이드로겔로 처리된 플롯 4 개, 1.0%, 1.5%, 2.5%, 5.0% w/w 농도의 바이오차를 가진 플롯 4 개, 저류 구조물을 부착한 샘플 4 개(저류 매트 샘플, 분해층 샘플, 저류판 샘플, 성장 기질에 하이드로겔 0.6% w/w 를 첨가한 저류판 샘플).

실험 결과는 노지와 비교했을 때, 초고흡수성 고분자로 토양을 개량하고 저류구조를 포함함으로써 성장기질 온도가 저하됨을 보여준다. 또한 누적 증발량의 증가와 보웬비의 현저한 감소는 시스템에 하이드로겔 및 또는 저류구조물을 단순 통합함으로써 잠열 방출이 크게

증가할 수 있음을 보여준다. 서로 다른 구성의 수용성 개량과 저류 구조로 개선되는 노지 자체의 성능 차이는 실내와 실외 환경 모두에서 냉각 효과 가능성을 보인다. 표면 온도 감소와 증발 개선은 현열 플럭스 감소뿐만 아니라 건물의 냉방 부하와 에너지 소비량의 큰 감소를 가져올 것이다.

옥상 녹화 성장 기판에 대한 토양 개량 적용 평가 결과 하이드로겔은 옥상녹화의 수분 저류 용량 증가와 결합하여 증발 및 잠열 방출을 증가시켜주는 첨가제임을 증명하였다. 하이드로겔로 개선된 토양의 에너지 기능은 개량되지 않은 토양에 비해 현저히 우수했다. 따라서 실내 및 실외 환경 개선을 위해 옥상녹화 성장 기질에 초흡수성 고분자 결합을 권장한다. 또한, 하이드로겔을 포함시키는 것은 도심 홍수 조절에 유리하고 옥상 식생 성립에도 이로울 수 있다. 잠재적 식물 발산 과정에 사용되는 저류 능력으로 인해 더 많은 양의 물을 제공할 수 있으므로 냉각 잠재력은 연구조사 결과보다 클 수 있다. 그럼에도 불구하고 하이드로겔이 옥상녹화 식생에 미치는 영향에 초점을 맞춘 추가 연구가 필요하다.

평가된 폴리머 농도 중 기질 내 하이드로겔 농도 증가는 플롯의 전체 에너지 기능에 긍정적인 영향을 미치는 것이 분명했지만, 최대치 결과 농도(0.8% 및 1.0% w/w)는 증발 및 잠열 방출 측면에서 매우 유사한 결과를 얻었다는 점이 중요하다. 따라서, 이 연구에서는 추후 연구에서 농도를 증가시켜도 증발 및 잠열전달은 개선되지 않을 것으로 예상한다.

뿐만 아니라 뿌리 부패의 가능성이 있기 때문에 식물들에게 잠재적으로 불리할 수 있다. 따라서 이 연구는 옥상녹화 성장 기질에 권장되는 하이드로겔 농도를 0.6%에서 0.8% w/w 사이로 제시한다.

반면 쌀겨 바이오차 적용은 역효과를 냈다. 전체적인 에너지 기능을 떨어뜨리고 토양 건조 속도를 높였기 때문에 쌀겨 바이오차(biochar)의 많은 이점에도 불구하고, 시스템 에너지 기능에 불리한 영향을 미치기 때문에 옥상녹화 첨가제로 권장하지 않는다. 이 연구는 특히 고농도의 쌀겨 바이오차를 사용하면 표면 온도가 상승하고 지열이 대기로 과도하게 방출될 뿐만 아니라 건물 실내 환경에 영향을 미칠 수 있으며 냉각 부하 증가와 건물의 에너지 소비량 증가에 영향을 끼칠 것으로 제안한다.

옥상녹화 에너지 균형에 대한 저류 구조물의 영향에 초점을 맞춘 연구 결과는 저류 구조물이 증발, 잠열 방출, 그리고 수분 유지 개선에 가장 중요한 구성 요소라는 것을 보여준다. 평가된 모든 구조물은 에너지 기능 향상에 가장 큰 영향을 미쳤다. 누적 증발 분석 결과, 저류 구조물의 적용으로 총 증발수의 양이 크게 증가하여, 세분층의 경우 0.39kg H2O, 저류 매트의 경우 0.67kg H2O, 저류판의 경우 0.8kg H2O, 저류판과 하이드로겔을 첨가한 경우 1.0kg H2O 의 증가가 있었다. 기질에 하이드로겔 증발된 물의 양의 이러한 유의한 증가는 방출된 잠열량의 큰 증가와 관련이 있으며, 따라서 현열 방출의 감소와 표면 온도 감소와 관련이 있다.

가장 적합한 구조물은 요구되어지는 옥상녹화의 목적에 기초하여 선택되어야 한다. 그러나, 연구 결론은 저류판이 설계 과정 중 주로 고려되어야 하는 구조임을 제안한다. 이는 폭풍우 조절과 도심 홍수 완화에 가장 효과적으로 기여할 뿐만 아니라 에너지 기능 관점에서 가장 높은 편익을 가져올 수 있다.

마지막으로, 수용성 개선과 저류 구조의 조합은 옥상녹화 기능을 최적화할 수 있는 옵션이다. 하이드로겔은 토양의 수분보유능력과 증발에 이용 가능한 물의 양을 증가시키지만, 이 저류 구조는 가뭄 기간 동안 저장된 물을 토양으로 다시 운반할 수 있기 때문에 홍수기간 중 넘치는 물을 저장하여 시스템 수분 보유 용량과 물 활용도를 증가시킬 것이다. 따라서 두 시스템을 결합하면 증발 및 잠열 방출을 강화할 수 있으며 동시에 표면 온도 감소와 홍수 저감 효과를 얻을 수 있다.

사실상 증식 기질 및 저류 구조는 옥상녹화 에너지 기능에 상당한 구성 요소이므로 시스템 설계 단계에서 신중하게 고려해야 한다. 적절한 구성요소를 선택한다면 건물과 환경 모두에 장기적 이익을 가져다 줄 것이다.

본 연구의 결과는 도심 지역의 불투수면적 감소를 목표로 옥상녹화 적용에 대한 법 개정이나 녹색 기반 시설에 투자하는 대규모 사업장에 대한 재정적 인센티브와 같은 새로운 정책 제안의 근거가 될 수 있다. 마지막으로 중요한 것은 옥상녹화가 증발 작용과 잠열 전달을

최적화시킴으로써 도시 환경을 향상시킬 수 있다는 것이다. 따라서, 이 연구는 도시 열섬 현상 완화에 대한 사회적 인식개선을 목표로 하는 캠페인의 기반이 될 수 있다.

그럼에도 불구하고, 조사된 플롯의 효과와 식물 성장과의 관련성을 평가하기 위한 추가적인 연구가 수행되어야 한다. 무엇보다 하이드로겔 첨가 토양이 옥상녹화 식생에 미치는 영향과 식물의 이용 가능한 물의 양을 최대화하는 동시에 뿌리 부패 방지하는 데 최적의 고분자 농도를 조사하는 것이 중요하다. 또한 실제 규모의 옥상녹화 시설에서 제안된 최적화 옵션을 구사하여 조사하는 것도 필요하다. 이와 같은 연구는 궁극적으로 본 연구를 보완하고 옥상녹화의 에너지 효율에 효과적인 개발을 촉진할 것이다.

Acknowledgements

Firstly, I would like to express my gratitude to my advisor, Professor Mooyoung Han for his support, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. For this I am sincerely grateful. Besides my advisor, I am very grateful to the rest of my thesis committee: Professor Yongju Choi and Professor Jongkwon Choe, for their support, insightful comments and hard questions which incented me to widen my research from various perspectives.

This thesis would not be possible without Waterfirst Lab family. I would like to thank you for all the encouragement you have given me during my tough times. To Thuy, for being my precious research mentor and good friend. To Esther, for being my sunshine on a rainy day. To Yunn, for being my very best chit-chatting partner. To Bang, for all his help and hard work. To Hakyung, for being a friend I could always count on. To Jooho, for being my ultimate guide and problem-solving savior. To Gippeum, for always supporting me and focusing on the brightest sides of life. To Jin, for being always there whenever I needed help. To Voni, for being the most kind and comforting colleague. To Janith, for all your advice and optimism you have brought to the lab. To Tian, for all the fun we had together. Thank you all, for everything.

To National Institute of International Education and Korean Government Scholarship Program for supporting my Master degree in Korea. I will always be grateful for giving me this opportunity.

To my wonderful Polish support team: Martyna Rajkowska, Anna Ludwiczak, Kinga Fluder, Sylwia Pękala and Paweł Rurkowski. For your unlimited support and faith in me, even if we were thousands of kilometers apart.

To my amazing Korea-based support team, Vivi Ha and Qamar Alhadidi, for being here with me. For your friendship, thoughtfulness and all the words of comfort. I hope we can always stay in touch!

To Jinpyo, my shooting star. For always being here and believing in me even when I stopped believing in myself. 너 덕분에 하루하루가 행복하다.

Last and most heartfelt acknowledgment, to my family. To my parents, my brother, grandparents and all the family members who have always cheered for me. I could not express how grateful I am to you. I love you, with all my heart. *Składam szczególne podziękowania dla moich wspaniałych Rodziców, mojego Brata Szymona, Babci, Dziadka oraz wszystkich pozostałych członków rodziny. Za Waszą bezwarunkową miłość, wiarę i bezgraniczne wsparcie. Dziękuję, że pozwoliliście mi rozwinąć skrzydła.*

I dedicate this achievement to my late grandfather, Jerzy Suchanecki.

Niniejszą pracę dedykuję mojemu śp. dziadkowi,

Jerzemu Suchaneckiemu.