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Munkhchuluun Battur

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Comparing thermal performance of green roof and shingle covered roof in Hungary, during summer.

Primary Supervisor: **dr. Andras Barczi PhD**

Senior lecturer

Author: **Munkhchuluun Battur**

KJ1IWX

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Abbreviations

CE: Carbon emission

CO_2: Carbon dioxide

CO: Carbon monoxide

COPD: Chronic obstructive pulmonary disease

EPS: Expanded polystyrene

GHG: Greenhouse gas

HVAC system: Heating, ventilation, and air conditioning system

LAI: Leaf area index

NO_x: Nitrogen Oxides

NO_2: Nitrogen dioxide

O_3: Ozone

$PM_{2.5}$: Fine particulate matter, particles are 2,5 microns or less in diameter.

PM_{10}: Particulate matter, particles are 10 microns or less in diameter.

SO_x: Sulphur oxides

UHI: Urban heat island

VOCs: Volatile organic compounds

1. Introduction

These days, we witness a scenario in which rapid economic expansion and urbanization combine to cause a decline in green spaces within cities and an increase in pollution sources, both of which contribute to the acceleration of global warming (Nor et al., 2021; Guatarri et al., 2020). However, densely populated urban areas that has characterized by numerous higher buildings, have started utilizing rooftops as green spaces (Wong and Lau, 2013). This is the implementation of green roof systems on a wide scale, which significantly helps to the building of sustainable cities. These systems offer many benefits, economic, environmental, and social dimensions (Teotónio et al., 2021). The benefits include mitigating air pollution, managing water runoff, reducing urban heat island effects and noise pollution, as well as promoting urban biodiversity. Green roofs have the potential to decrease greatly amount of energy that required to cool and heat buildings by utilizing processes such as evapotranspiration, photosynthesis, solar shading, and thermal insulation (Kostadinović et al., 2022).

The green roof minimizes the quantity of sunlight striking the roof. This contributes to lower indoor and outdoor temperatures in the building and urban area, depending on the type of vegetation, depth, and type of growing medium, and local environment (Perivoliotis et al., 2023). This, in turn, serves to minimize a building's cooling load, resulting in lower air-cooling requirements, energy consumption, and atmospheric carbon emission (Mukherjee et al., 2013). Moreover, extensive research has been carried out worldwide to assess the impact of green roofs on reducing the energy requirements for heating and cooling in both commercial and residential buildings. Findings can differ and occasionally conflict with one another. Several aspects impact the effectiveness of green roofs. These include the climatic zone, the building materials, seasonal fluctuations, and the specific green roof materials that are utilized (Pianella et al., 2017).

Growing up in a city, I have personally witnessed the challenges of urbanization such as heat shock, air pollution, excessive run off water and many other environmental problems, and have been motivated to find ways to enhance our urban environment. Cities have become the primary residence for most of the world's population, a trend expected to continue in the future. In the concrete jungle of densely packed buildings and expansive pavement that dominates city landscapes, I observed the necessity for inventive solutions to urbanization's negative effects. In this context, I investigated green roofs as a sustainable alternative. Cities lack the space required to install additional green lands such as parks and gardens in order to address environmental concerns. Utilizing rooftops for gardens is a clever concept since they occupy a great amount of space in urban areas. Therefore, my dedication lies in researching green roofs and their impact on thermal performance, with the ultimate goal of creating healthier and more resilient cities for present and future generations.

Furthermore, I participated in the "Urban Horticulture" summer school project in Bulgaria through the Erasmus Plus Program in 2023. This experience showed me how green spaces benefit communities, providing places for relaxation and stress relief. It was inspiring to see how these areas become cherished by citizens and foster a sense of community. This has strengthened my commitment to creating vibrant urban environments with green elements.

This thesis work investigates the thermal performance of green roofs compared to conventional roofs. The research measurements were carried out on the campus of the Hungarian University of Agriculture and Life Sciences, where samples of both green roofs and conventional roofs were installed for analysis.

2. Literature review

2.1 Urbanization, climate change and environmental aspects

The environment and climate worldwide have been significantly impacted by urbanization and leading to a growth of climate change effects (Bazrkar et al., 2015). Basically, global warming is the increase in temperature of the Earth's land and ocean surfaces that has occurred since the middle of the twentieth century. This phenomenon mostly results from human activities that release greenhouse gases into the atmosphere, including carbon dioxide, methane, and nitrous oxide. And consistently rising temperatures are the cause of many other long-lasting effects of global climate change (Helbling and Meierrieks, 2022).

2.1.1 Introduction to urbanization and urban climate change

Urbanization is a long-term social migration process from traditional rural areas to modern urban areas (Pathak and Dubey, 2023). As cities expand, it comes with its challenges and benefits to people and environment. Despite the challenges, urban areas offer us economic growth, opportunities for job creation, access to education and healthcare, transportation, social security and interaction and technological advancement. However, these opportunities has been accompanied by challenges including inadequate energy consumption, deficient urban infrastructure, and substandard delivery of essential services. These issues converge to produce adverse environmental effects, including traffic congestion and the expansion of urban areas. Cities play a significant role in the degradation of the region's natural surroundings. They act as heavy consumers of resources and persistent emitters of pollution. (Elmqvist et al., 2013; Sharif et al., 2023; Thallak and Dhindaw, 2016). Over the last century, the global population has rapidly urbanized, and the rate of urbanization is expected to reach roughly 70% by 2050, and the majority of the increase is predicted to occur in small and medium-sized cities, not megacities. (Sharif et al., 2023; Elmqvist et al., 2013).

As Figure1 shows the predicted growth of urbanization, in 2018, more than half of the population in North America lived in cities with over 500 000 residents, and one out of every five individuals resided in cities with populations exceeding 5 million. Latin America and the Caribbean had the highest concentration of people living in mega-cities, with 14,2% of the region's population residing in six cities each having over 10 million inhabitants. Meanwhile, in both Africa and Asia, rural areas were home to more than half of the population in 2018, although this proportion is decreasing. It is projected that between 2018 and 2030, the number of cities with populations exceeding 500 000 will increase by 57% in Africa and by 23% in Asia. (The World's Cities in 2018, 2018).

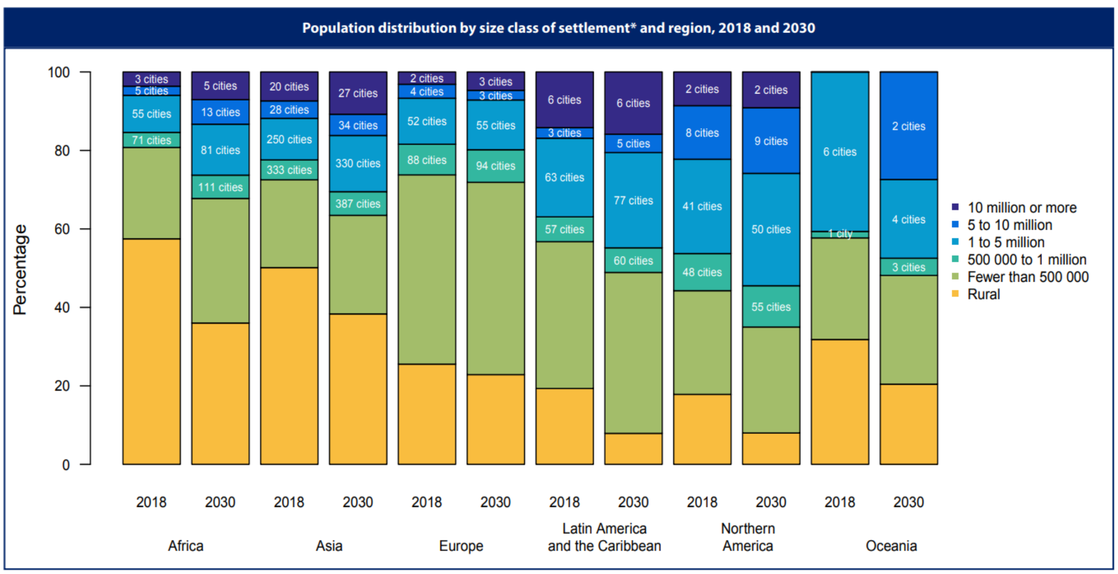

Figure 1. Population distribution by size class of settlement and region, 2018 and 2030 (The World's Cities in 2018, 2018).

Climate change is a pressing concern in today's world, posing significant challenges due to its effects such as rising temperatures and unpredictable weather patterns, which have certain impacts on urban regions (Shivanna, 2022). The urban population is held responsible for approximately 75% of global direct final energy consumption and carbon dioxide (CO_2) emissions. As an example, within the European Union, urban areas account for 30% of water usage and 40% of final energy consumption. Additionally, they contribute to 30% of CO_2 emissions and are responsible for 30% of waste production (Pathak and Dubey, 2023).

Notably, climate change in urban areas has had an impact on human health, livelihoods, and critical infrastructure (Kyprianou et al., 2023). There are numerous climate change-related risks for urban areas, including rising sea levels, storm surges, heat stress, extreme precipitation, and inland and coast flooding. These dangers are heightened for those who live in informal settlements, where there is a lack of adequate housing, basic services, and reliable infrastructure. Due to their higher population density, urban areas are more vulnerable to extreme climatic shocks such as heatwaves, hurricanes, changes in precipitation patterns, pollution, diseases, and so on (Revi et al., 2014; Pathak and Dubey, 2023). Heat waves, wildfires, urban drought/flooding, and extreme climatic events, for example, are being experienced in the northern and southern hemispheres during 2018 and 2019, primarily in the towns and cities of Australia, California, and Chile. Climate change models predict that in the cities of Europe, Africa, and South America, the mean maximum temperature will rise by 2-8 °C in the coming decades, resulting in frequent droughts (Pathak and Dubey, 2023).

Cities are particularly vulnerable to these changes for a variety of reasons. For starters, cities are commonly located in common topographic settings—near sea level, in valleys and basins, and near coasts—that expose them to a variety of hazards. Second, the high population density and dense urban infrastructure increases their vulnerability to projected climate change. Finally, the urban effect on local climate, such as the urban heat island, will amplify long-term climate changes such as global warming and heatwaves (Stewart and Mills, 2021).

2.1.2 Urban heat island effect

The urban heat island (UHI) phenomenon was discovered by Luke Howards, a British scientist, in London in 1818. It has been recognized in many countries and regions around the world (Sütçüoğlu and Önaç, 2023). UHI intensity refers to the temperature contrast between urban and neighboring rural regions. The rise in temperature within urban areas can be attributed to various factors, including increased heat absorption and retention caused by factors such as building density, thermal characteristics, and the reflective properties of urban materials. Additionally, the absence of greenery and water bodies, along with the heat generated by human activities like vehicles and Heating, Ventilation, and Air Conditioning (HVAC) systems, contributes to this temperature differential between urban and rural environments (Salvati and Kolokotroni, 2023). The physical configuration of cities (including topography, spatial morphology, and building density), the materials used in the construction of buildings, pavements, and roads, the flow of air through the street network, and heat-producing human activities such as transportation and industry all contribute to the formation of UHIs (Khan et al., 2022). Higher air temperatures, usually measured at street level, are the most common indicator of urban overheating. Increased air temperatures can have a variety of negative consequences, including increased outdoor heat stress (both during the day and at night), deteriorated air quality, increased energy consumption for indoor cooling, and even an increase in mortality rates (Khan et al., 2022). The UHI effect tends to be advantageous for large cities, with its intensity typically correlating with the city's latitude, population size, and level of development. UHI intensity fluctuates throughout the day and across seasons, reaching maximum values of nearly 10 °C and averaging between 2 to 4 °C (Piracha and Chaudhary, 2022).

Higher urban temperatures are associated with greater energy consumption for cooling buildings, increased heat stress in humans, and changes in natural ecosystems. Furthermore, the UHI occurs in conjunction with other urban effects on air pollution, airflow, hydrology, and so on (Stewart and Mills, 2021).

2.1.3 Carbon emission and greenhouse gases generated by urbanization

Global warming is a serious threat to human health, life, and the living environment. Carbon emissions (CEs) are the primary cause of global warming and reducing them is a critical step in mitigating their negative effects, according to global institutions and researchers (Chen et al, 2023). To enhance the quality of human life and mitigate the strain on the environment, it is crucial to decrease the utilization of natural resources while also improving their efficiency. Cities, which are often home to most of a nation's population and economic activity, serve as hubs for industries and commerce. As a result, cities tend to have the most significant resource consumption footprints, encompassing both direct and indirect greenhouse gas emissions. This substantial impact on both the social and natural environment has made cities a frequent focus of sustainability policies (Liu et al., 2023).

Since 1970, the world has experienced rapid urbanization development, while cumulative CO_2 emissions from human activities have accounted for roughly half of the total since the Industrial Revolution (Wang et al., 2021). The global urbanization level increased by 18,7% between 1970 and 2018. Global CEs have increased by 40% since the twenty-first century, from 2000 to 2019. In 2019, global and per capita CEs reached new highs of 34,36 billion tons and 4,42 tons, respectively. Furthermore, research has shown that global CEs in 2020 would be about 5% lower than in 2019. However, large-scale urbanization will continue to grow in the future. As a result, implementing low-carbon urbanization can contribute to a significant breakthrough in achieving sustainable economic-ecological-social development while also improving human well-being (Chen et al, 2023).

In Figure 2, global per capita CEs were 1,234, 1,276, and 1,272 in 2000, 2010, and 2019, respectively, which indicates an increasing trend during the study period. Per capita CEs were high in North America, Europe, and north and west Asia. Per capita CEs were relatively low in Africa, South America, and southern Asia. The State of Qatar had the highest per capita CEs among the 125 countries during the study period, with per capita CEs of 15,508, 10,088, and 10,302 in 2000, 2010, and 2019, respectively. The Republic of Burundi had the lowest per capita CEs at around 0,007, which remained relatively stable throughout the study period. The CEs of developed and major oil-exporting countries per capita were relatively high, while those of developing countries were relatively low (Chen et al, 2023).

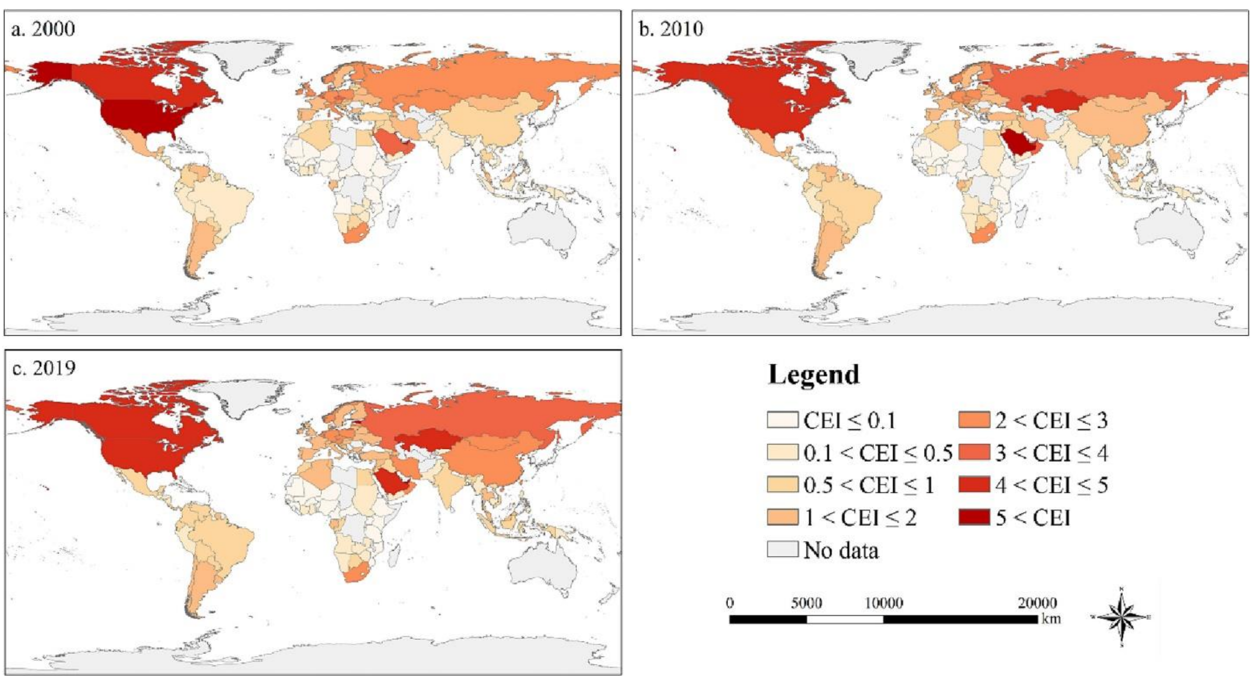

Figure 2. Spatial patterns of global per capita CEs from 2000 to 2019 (Chen et al, 2023).

Urban carbon emissions can be used to analyze energy consumption and its environmental impact and make a notable contribution to a country's overall carbon emissions. Currently, energy, industry, agriculture, transportation, and buildings are the leading drivers of urban carbon emissions. (Zhu and Hu, 2023). Several interdisciplinary studies have explored the interconnectedness of environmental, economic, planning, and architectural disciplines. They revealed the factors such as the economy, demographics, technology, and policies, including elements like population size, urbanization trends, and energy consumption, collectively influence carbon emissions (Lantz and Feng, 2006; Haouas et al., 2023). Carbon emissions typically increase when urbanization and the economy expand. However, when economic progress shifts from extensive to low-carbon practices, there is a tendency for energy consumption to become more efficient and leading to a decrease in carbon emissions (Sun and Huang, 2020).

Construction is one of the major industries and activities with the highest carbon footprint. According to the Intergovernmental Panel on Climate Change's 4th Assessment Report, greenhouse gas emissions from buildings amounted to 8,6 billion tons of CO_2 equivalent in 2004. Some predictions suggest this could rise to 15,6 billion tons by 2030, marking a 26% increase. These emissions from buildings make up a significant portion which is estimated at 30-40% of the total greenhouse gas emissions (Sizirici et al., 2021). The emissions from buildings consist of two distinct types: embodied emissions and operational emissions. Embodied emissions are also referred to as implicit emissions and it entails the carbon emissions generated during the production, transportation, construction, and eventual demolition of buildings. On the other hand, operational emissions encompass the carbon emissions originating from direct energy consumption within buildings, such as indoor cooking, lighting, electrical appliances, and heating (Zhu and Hu, 2023; Liu et al., 2023). Carbon emissions from the building life cycle are the total CO_2 emissions from material manufacturing, construction, operation and maintenance, and destruction and disposal. From the entire life cycle of a building's perspective, carbon emissions are reflected in its primary energy consumption. Therefore, it's possible to calculate the carbon emissions at each stage of construction. Comparative data analysis across many stages can help us understand low-carbon buildings and make better decisions. (Wang et al., 2023).

Multiple research initiatives have revealed that transportation energy accounts for most of the urban energy consumption and that this energy has a strong correlation with intracity urban form

(Long et al., 2013). Transport carbon emissions are influenced by several important factors, such as the mix of land use, proximity to employment centers, infrastructure development, and accessibility to transportation hubs. These factors play significant roles in shaping transportation behaviors and patterns, thus affecting the amount of carbon emissions generated from transportation activities (Zhu and Hu, 2023). As of 2022, the global vehicle count was estimated to be 1.45 billion. This figure surged from 670 million in 1996 and a mere 342 million in 1976. If the current growth trend continues, it is estimated that by 2036, there will be around 2.8 billion vehicles worldwide. Vehicle usage and travel distances have been consistently increasing in countries around the world. (Piracha and Chaudhary, 2022). According to the World Energy Outlook, between 2004 and 2030, the transportation sector will be responsible for 30% of the increase in petroleum consumption. The research claims that the growing reliance on motor cars for transportation is contributing to the depletion of resources and the acceleration of global warming (Cheng et al., 2015). The exhaust emitted by motor vehicles consists of a hazardous combination of carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter (PM_{10} and $PM_{2.5}$), numerous volatile organic compounds (VOCs), and ozone. According to a report by the United States Environmental Protection Agency, vehicles' emissions can contain as many as 1162 distinct compounds. These emissions have detrimental effects on the health of millions of individuals, especially those residing near heavily trafficked roads (USEPA, 2021).

2.1.4 Urban air pollution

The UHI effect leads to a variety of consequences such as shorter sunlight duration, lower humidity, higher chances of precipitation, and the formation of dust domes. All of these hinder the dispersion of pollutants in urban atmospheres. Air pollution can originate from various sources, including both natural phenomena and anthropogenic activities. However, the main sources of air pollution today are primarily human-made, arising from activities such as agricultural incineration, industrial processes, and emissions from transportation (Ku and Tsai, 2023). The collective impact of automobiles, industrial activities, and urban living patterns results in the substantial emission of nitrogen oxide, carbon dioxide, and dust into the atmosphere. These pollutants play a role in absorbing thermal radiation emitted from the Earth's surface, thereby contributing to the phenomenon of global warming, and further intensifying the temperature of the atmosphere (Brunekreef and Holgate, 2002). Fundamentally, the complex composition and characteristics of pollutants, also referred to as aerosol particles, can detrimentally impact air quality, alter the physical and chemical properties of the atmosphere, and pose a threat to human health (Manisalidis et al., 2020). Moreover, aerosol particles have the power to change the surface and atmosphere's radiation balance. While they have the capacity to decrease surface temperatures by diminishing the incoming shortwave radiation, they can also absorb and emit radiation more effectively than water vapor and greenhouse gases, potentially resulting in an elevation of longwave radiation energy reaching urban areas. (Yang et al., 2021).

It's important to highlight that controlling greenhouse gas emissions (GHG) and air pollutants during the operational phase of building is more challenging compared to the construction and demolition stages. This difficulty stems from various factors such as climate change, urbanization, and shifts in energy infrastructure (Zheng and Chen, 2024). Climate change can impact the energy consumption of buildings by altering the demand for heating and cooling, thereby potentially increasing GHG and air pollution. This is because most of the energy used for regulating temperature, such as electricity, comes from fossil fuels like coal, oil, and natural gas. (Zheng et al., 2019). Various factors can impact air pollutants, such as changes in weather conditions, alterations in chemical composition, and shifts in natural emissions caused by biological changes. (Zheng and Chen, 2024; D'Amado et al., 2014).

2.1.5 Urbanization and human health effects

As cities undergo urbanization, they experience growth and progress, providing inhabitants with opportunities for employment and access to resources. However, this process can also encourage unhealthy lifestyle choices and increase exposure to environmental stressors like traffic congestion and air pollution. Moreover, urbanization may amplify existing inequalities in access to infrastructure and resources within communities.

Due to the rising global urban population, the likelihood of heat-related health risks in metropolitan and larger urban areas has grown in proportion. A recent analysis, encompassing data from 1 300 cities worldwide, suggests that approximately one-fourth of the global population, equivalent to nearly 1,7 billion individuals, faces exposure to extreme heat (Piracha and Chaudhary, 2022). Heat-related mortalities are often underestimated because heat stress contributes to various apparent causes of death such as cardiovascular, respiratory, and cerebrovascular failures.

Additionally, high temperatures are linked to an increase in mental health emergencies. Prolonged exposure to intense heat worsens mental health conditions and can cause serious medical complications (Basu et al., 2018).

According to research from 2017, fine particulate matter ($PM_{2.5}$) was linked to approximately 2,9 million premature deaths attributed to conditions such as ischemic heart disease, stroke, chronic obstructive pulmonary disease (COPD), lung cancer, lower respiratory infections, and type 2 diabetes. Additionally, ground-level ozone was estimated to be associated with 472 000 premature deaths from COPD. Major human-caused sources of air pollution worldwide include transportation, power generation, residential fuel combustion for energy purposes (such as cooking, heating, and lighting), industrial operations, and agriculture (Anenberg, 2019).

2.2 Green roof

To tackle urban environmental concerns, a wide range of environmentally friendly technologies and nature-centric solutions have been created and implemented. These include the use of renewable energy sources, energy-efficient building techniques, methods for reducing pollution in the air and water, the development of green metropolitan areas, and the growth of environmentally friendly infrastructure (Shafique et al., 2018). The use of rooftops as green spaces has become increasingly common in densely populated metropolitan regions that are characterized by a large number of high-rise structures (Wong and Lau, 2013).

2.2.1 Introduction of green roof

Green and blue spaces in cities promote health by providing opportunities for physical activity, stress relief, and social interaction, which can be categorized as cultural ecosystem services. They also provide a variety of regulating ecosystem services that can be viewed as nature-based solutions to urbanization-induced challenges. On hot summer days, urban trees and other vegetation provide cooling through shade and evapotranspiration, reducing the impact of the UHI. Urban greenery, including parks, gardens, playgrounds, and cemeteries, can enhance air quality by effectively filtering out air pollutants. Moreover, these open urban spaces serve as permeable surfaces, aiding in rainwater absorption during heavy rainfall, thereby contributing to effective water management. These combined ecosystem services hold the promise of enhancing the well-being of city dwellers, especially vulnerable populations like children and the elderly (Kabisch et al., 2017).

Green roofs are man-made ecosystems offering a nature-inspired approach to tackling environmental issues like climate change and UHI (Mihalakakou et al., 2023). Fundamentally, rooftops are covered with various types of vegetation or plants, planted on a growth medium or substrate. This architectural concept aims to promote the growth of vegetation on building rooftops, offering numerous social, economic, and environmental advantages. Typically, a green roof comprises several elements, such as vegetation, substrate, filter layer, drainage material, insulation, root barrier, and waterproofing membranes (Shafique et al., 2018). Nevertheless, the densification of cities has led to a shortage of urban green areas. These green spaces are crucial in urban environments as they offer vital ecosystem services to residents and contribute to preserving wildlife habitats (Joshi and Teller, 2021).

2.2.2 Types and components of green roof

Green roofs commonly consist of several layers: vegetation, comprising plants that enhance air and runoff quality, serve as a moisture barrier, and aid in energy conservation; substrate, providing a growth medium for plants; a filtration layer, separating the substrate from drainage material ; drainage material, which improves the thermal characteristics of green roofs and regulates air and water balance; a root barrier, safeguarding the structure from damage; and a waterproofing layer, essential for protecting the building's integrity (Shahmohammad, 2022; Perivoliotis et al., 2023).

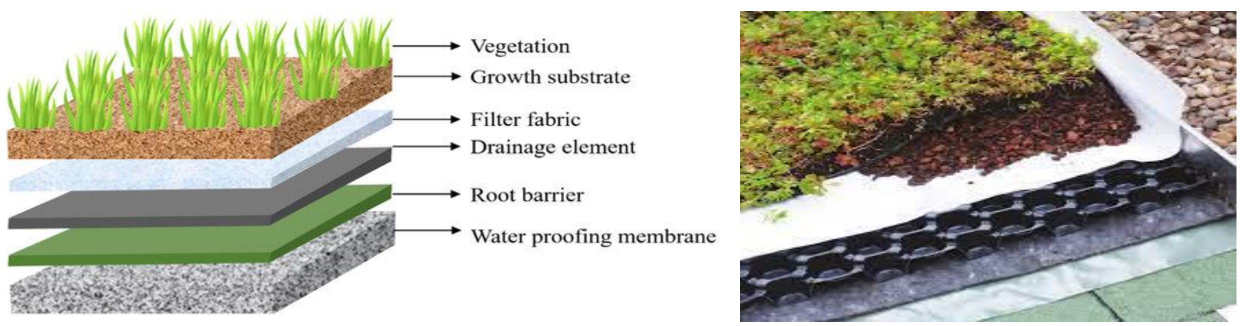

Figure 3. Green-roof design (Hussain et al., 2020; Bauder).

When it comes to substrate depth, green roofs can be divided into three categories: extensive, which has a shallow soil substrate of 15 to 20 cm, and short plants including are used. They require minimal upkeep as their purpose is ecological, not aesthetically pleasing. Individuals rarely or never interact with an extensive green roof, and the plants there don't need much special care; semi-intensive, which has medium maintenance and irrigation needs; and intensive, which has a deeper soil depth of up to one meter and can support large trees and shrubs. Roofs are intended to work more like a traditional terrestrial garden with a variety of plants that need individualized care, they demand a high level of maintenance. necessitates significant maintenance and irrigation (Perivoliotis et al., 2023; Ampim et al., 2010; Kader et al., 2022).

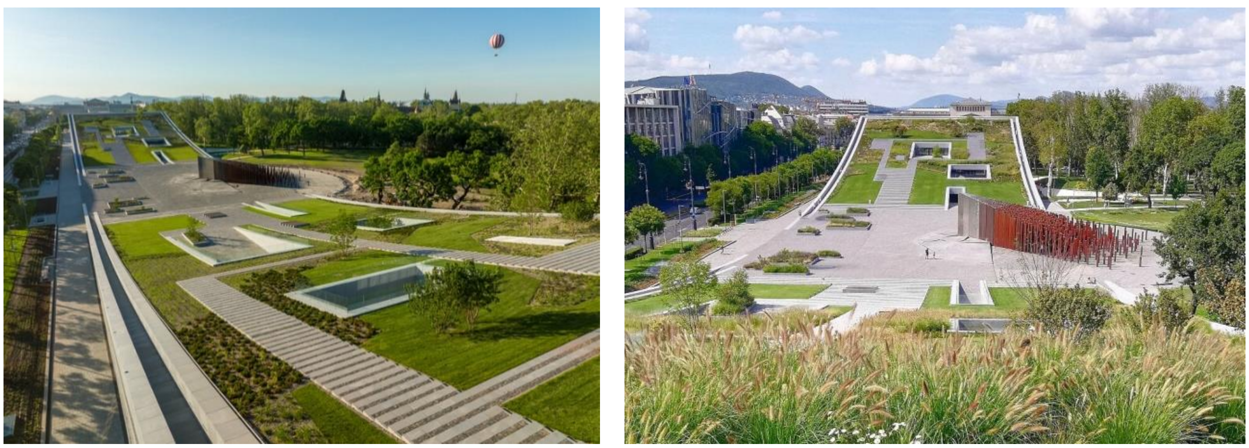

Figure 4. Intensive green roof example in Budapest, Hungary. Museum of Ethnography (Contemporist, 2022)

Figure 5. Extensive green roof examples in Gyor, Hungary. Family houses and Apartments. (ArchiGreen, 2016)

Researchers have identified many key traits of plants suitable for extensive green roofs: (1) rapid establishment and quick reproduction; (2) low height and a cushion or mat-like growth habit; (3) shallow but spreading root systems; and (4) succulent leaves or the ability to retain water for example moss-sedum, sedum-moss-herbaceous plants, sedum-herbaceous-grass plants, and grass-herbaceous plants and the depth of substrate is 2-20 cm. The following four plant species can be used in semi-intensive green roofs: grasses, herbaceous plants, wild shrubs, coppices, and shrubs and coppices. These species prefer a deeper growing substrate, around 12–100 cm (Banting et al., 2005). Lastly, the seven main categories of plants that thrive on intense green roofs are: The landscape consists of lawn, shrubs, and coppices at different heights (low, medium, tall), large bushes, small trees, medium trees, and giant trees. Their ideal growing depth is 15-200 cm (Banting et al., 2005; Yildirim et al., 2023).

An extensive green roof is the least expensive choice among the three types of green roofs in terms of both installation and maintenance, as it can be self-sustaining. Along with the fact that extensive green roof implementation is more convenient and adaptable, most research has been conducted on the effects of severe environmental conditions on such roofs (Yildirim et al., 2023). The water retention capacity of various vegetation types under extensive green roofs ranged from 40% to 60% of the precipitation. The amount of water retained by semi-intensive and intense green roofs is determined by the size of their coverage (Banting et al., 2005). (Simmons et al., 2008) investigated revealed how the size of a rain event and the intensity of rainfall impact water retention. Green roofs effectively captured and retained rainfall episodes of less than 10 mm. The green roof retention varied from 88% to 26% in response to 12 mm of rainfall. The retention depends on the substrate and the type of drainage.

2.2.3 Environmental benefits of green roof

Green roofs provide environmental and economic benefits such as managing stormwater, conserving energy, reducing the UHI effect, improving water quality, and preserving biodiversity (Raimondi and Becciu, 2020). Traditional roofs facilitate rapid rainwater runoff, exacerbating issues such as flooding, erosion, and combined sewer overflows that can lead to untreated sewage discharge into water bodies. In contrast, green roofs are essential for mitigating these problems by absorbing rainwater, delaying runoff, promoting evapotranspiration, and improving stormwater management efficiency (Kader et al., 2022). Moreover, the presence of soil and vegetation on green roofs may reduce the pollution of stormwater runoff by filtering and absorbing pollutants (Zhang et al., 2015). Green roofs can help to neutralize acidic rainwater and drastically reduce heavy metal runoff. Extensive green roofs have been shown to decrease lead by 99%, zinc by 96%, cadmium by 92%, and copper by 97%. This reduction is mostly the result of retained contaminants rather than filtration. The nutrient levels in runoff are determined by fertilization techniques (Jusić et al., 2019). Some studies indicate that runoff retention values from green roofs typically average around 67%, varying between 50% and 80%. This represents the amount of rainfall controlled by the green roof after a rain event. Variations in runoff retention among extensive green roofs are influenced by several factors, including climate conditions, roof designs, slope, study duration, substrate depth and type, vegetation, and the lifespan of the green roof (Shafique et al., 2018).

Green roofs make a significant contribution to reducing the carbon footprint by decreasing greenhouse gas emissions, leading to a cleaner atmosphere and reduced noise pollution. City air frequently contains high amounts of contaminants that are detrimental to human health (Mayer, 1999). Plants remove pollutants in several ways. They can capture ambient CO_2 directly from the environment through photosynthesis, which is then retained in plants and substrates as above-and below ground biomass as well as in organic matter within substrate (Agra et al., 2017). Moreover, green roofs indirectly mitigate air pollution by reducing surface temperatures through transpiratory cooling and shading, thereby lowering the occurrence of photochemical reactions that produce pollutants like ozone in the atmosphere. By minimizing the need for air cooling, a lower energy requirement leads to decreased power plant emissions (Rosenfeld et al., 1998).

2 000 square meters of natural grass on a green roof can potentially eliminate up to 4 000 kilograms of particulate matter. For instance, an average gasoline-powered car emits around 0,01 grams of particulate matter per mile. If a car travels 10 000 miles annually, it releases 0,1 kilograms of particulate matter yearly. Thus, one square meter of green roof could counterbalance the yearly emissions of one car. In a study by Clark et al. (2005), it's projected that if 20% of industrial and commercial rooftops in Detroit were green roofs with sedum plants, over 800 000 kilograms of nitrogen dioxide (NO_2) emissions, equivalent to 0,5% of the area's total emissions, could be removed annually. Similarly, in Singapore, above a green roof, there was a reduction of 37% in sulfur dioxide and 21% in nitrous acid (Rowe, 2010). Conventional roofs are often hard surfaces, so adopting green roofs has the potential to lessen noise pressure from highways and other sources

in these regions. Vegetation, together with the growing substrate, will absorb sound waves more effectively than a hard surface (Renterghem and Botteldooren, 2008).

The decrease in temperature can be attributed to a key advantage of green roofs, which is shielding the structural layers from solar radiation. This leads to a mitigated temperature fluctuation compared to traditional roofs, which reflect a portion of solar radiation and absorb a significant portion of solar heat through photosynthesis, resulting in elevated surface temperatures and increased thermal stress on materials, thereby diminishing their longevity (Baryła et al, 2019; Schade et al., 2021). They also offer benefits, such as mitigating the UHI effect by improving indoor thermal comfort and reducing the demand for cooling systems, resulting in energy savings. The proliferation of green roof vegetation in cities has increased floral availability and enhanced animal diversity, highlighting the superiority of green roofs over conventional ones (Kader et al., 2022).

By utilizing a layer of growing medium, they effectively insulate the building envelope, while the vegetation provides shade and contributes to transpiration cooling. Additionally, the increased thermal mass of green roof systems further improves their ability to regulate temperature. Field observations in Japan during the summer have demonstrated a considerable reduction in roof surface temperature, from approximately 60 °C to 30 °C, attributable to the presence of green roofs (Schade et al., 2021).

The energy demand for cooling buildings has surged in recent years, with buildings now accounting for 30–40% of global energy consumption according to the International Energy Agency. In Singapore, approximately half of the electricity generated is consumed by buildings, with cooling alone representing about 30% of the country's total electricity consumption. The rising urban temperatures exacerbate the risk of overheating and indoor discomfort, largely influenced by the heat flux and energy retention of building materials. Roofs, constituting 20–25% of urban surfaces, are particularly impactful as studies indicate that solar radiation can elevate their outer surface temperatures by 50–60 °C (Yang et al., 2018).

Green roofs have the potential to lower cooling demands by as much as 70%, leading to a reduction in indoor temperatures of up to 15°C and significantly enhancing thermal comfort. Furthermore, their environmental advantages extend to diminishing concentrations of pollutants such as $PM_{2.5}$,

PM_{10}, ozone (O_3), and NO_2, as well as sequestering carbon and mitigating urban noise pollution (Mihalakakou et al., 2023).

2.2.4 Green roof's effect on human health.

As climate change worsens, there is a noticeable decline in human health, both physically and mentally, which underscores the urgency of addressing climate-related challenges for the stability of healthcare systems (O'Hara et al., 2022). Moreover, urbanization not only involves population growth but also affects the overall "city health" and social atmosphere, emphasizing the interconnected relationship between environmental factors, urban development, and public well-being (Rezaei et al., 2021). People residing in areas lacking green spaces may face enhanced vulnerability to the negative impacts of urban stress due to the absence of nature-based coping mechanisms. The global recognition of the benefits provided by green spaces has heightened, as they positively affect citizen satisfaction, spiritual and physical health, and sustainability. Additionally, increased greenery in neighborhoods fosters social cohesion, resulting in reduced aggression and violence (Grahn and Stigsdotter, 2003).

In addition to the environmental threats posed by urbanization, healthcare systems contribute to climate change through their greenhouse gas emissions, stemming from energy consumption, product manufacturing, and transportation (Eckelman and Sherman, 2016). Urban healthcare buildings, particularly hospitals, stand as significant contributors to greenhouse gas emissions, ranking as the "second-most energy-intensive commercial buildings" in the United States after food production. These emissions not only exacerbate climate change-related health issues but also contribute to environmental degradation (Alotaiby and Krenyácz, 2023). Therefore, particularly healthcare buildings, including hospitals, present an opportunity to lead sustainable initiatives, especially concerning the implementation of green roofs. Green roofs on urban hospitals can serve to mitigate environmental concerns affecting public health by providing ecosystem services. With their large, flat, often unutilized roof spaces, urban hospitals offer an ideal environment for the implementation of green roofs, aligning with both environmental and public health objectives (Coutts and Hahn, 2015; Feng and Hewage, 2018). Research conducted by Aprelle C. O'Hara and colleagues suggests that having green spaces in hospitals brings many benefits. These include helping to reduce stress and improve mental health, encouraging social interaction and community bonding. Having access to green areas also encourages physical activity, lowers the incidence of cardiovascular and respiratory illnesses, reduces the need for pain relief, and shortens the time patients stay in the hospital. Notably, when green spaces are included into hospital surroundings, both patients and staff report higher levels of satisfaction (O'Hara et al., 2022).

2.2.5 Challenges of implementing a green roof.

Even though green roof has many advantages, several barriers can constrain the implementation of GRI (Green Roof Infrastructure), including inadequate government policies, insufficient technological advancement, unsound economic benefit assessments, and reluctance among individuals (Zhang and He, 2021). Most notably, the fundamental challenges remain similar, owing to an absence of supporting regulations, a lack of experience with green roofs, and expensive installation costs. The current authors feel that regulatory concerns should be addressed through the government's technical authority, which has the capacity and legal foundation. While the rules are being finalized, the development of green roof technology in accordance with the climate features of ASEAN countries must be prioritized by utilizing appropriate green roof technology to reduce installation costs for building green roofs (Pratama et al, 2023).

Despite the recognized potential of green roofs for pollution control and restoring natural hydrology in urban areas, significant challenges persist, hindering their widespread adoption. While numerous studies extol the social, environmental, and economic benefits of green roofs, barriers such as high initial costs, limited awareness of construction and maintenance, and the lack of universally applicable designs impede their implementation, particularly in underdeveloped nations. Addressing these challenges requires research attention, particularly in adapting green roof designs and plant selections to diverse climates. Furthermore, factors like construction expenses, reduced polymer use and disposal, maintenance costs, local research limitations, roof leakage issues, and interdisciplinary collaboration gaps need consideration for effective green roof integration in urban environments (Dauda and Alibaba, 2019).

Retrofitting existing buildings presents a significant challenge, particularly for those with steel pitched roofs, as it often entails extensive structural modifications and substantial costs. For instance, ensuring the integrity of waterproofing is crucial to prevent interior damage caused by water leakage from drainage systems and potential root puncture. Proper selection of waterproofing membranes, root barriers, and drainage layers is essential for mitigating such risks.

Additionally, green roofs require meticulous operation and maintenance to avoid system failure, which can manifest as leaks, plant loss, pesticide presence, inadequate drainage, soil erosion, and shifts in plant and soil communities over time. Limited resources for long-term maintenance pose a challenge for building owners. Moreover, climate factors such as heavy rainfall, high temperatures, and strong winds can further impede the success of green roofs, potentially leading to stagnant water accumulation, heat stress on plants, and damage to vegetation and soil (Shams et al., 2018).

2.3 Green roof thermal performance and case studies

In response to the growing demand for more efficient energy consumption, city planners in various regions of the world have recently adopted strategies that involve the adoption of infrastructures that are both more efficient and more sustainable (Yildirim et al., 2023). Buildings and roofs are primary energy consumers. One way to make buildings sustainable is by investigating how green roofs perform in different climates. This in-depth study will help us understand their thermal efficiency better and unlock their full potential in creating eco-friendly structures (Liu et al., 2023).

2.3.1 Concerns of building's energy consumption

The construction industry is critical in the search for increased energy efficiency across all human activities to promote sustainable resource consumption. It accounts for nearly 40% of both energy consumption and the emission of pollutants into the atmosphere (Cirrincione et al., 2020). Globally, the building sector's energy consumption constitutes 30% of the final energy consumption (Delmastro and Chen, 2023), whereas in Europe, buildings account for 40% of total energy consumption and 36% of greenhouse gas emissions, which are mostly caused by construction, use, repair, and demolition (European Commission, 2020).

In addition to standard design strategies inherent to bioclimatic architecture principles, such as spatial organization, window-to-wall ratio, orientation, thermal mass, and operational management (Underwood and Yik, 2004), significant energy savings in buildings are primarily attributed to two main components: technical systems HVAC and the building envelope, which interact synergistically. While reducing HVAC-related energy consumption often involves active systems requiring further energy input, passive systems within the building envelope, which independent of energy, can effectively reduce energy consumption and decrease the HVAC system's requirements and size (Cirrincione et al., 2020). Additionally, occupants' behaviors and attitudes play a significant role in energy conservation (Caniado and Gasparella, 2019).

2.3.2 Parameters of green roof thermal performance

Some of the most essential aspects influencing a green roof's efficiency on thermal load include the type of plants grown on the roof surface, soil properties and moisture content, and the leaf area index (LAI) (Seyedabadi et al., 2021). The LAI is a crucial vegetation biophysical parameter, representing the ratio of leaf area to the ground surface area per unit (Zheng and Moskal , 2009). The surfaces of leaves serve as the main interface for the exchange of energy and mass. Essential processes like canopy interception, evapotranspiration, and gross photosynthesis are directly influenced by the LAI. (Fang and Liang, 2008).

The cooling advantage provided by green roofs comes from both the vegetation and the substrate it grows in. Many studies have defined the thermal properties of green roof substrates, which offer insulation against solar energy. However, understanding how the vegetation itself contributes to building cooling is more complex and hasn't been fully explained yet (Junjun et al., 2019). Transpiration occurs when trees and plants absorb water from their roots and cool their surroundings by releasing water vapor through their leaves (EPA, 2023). Choosing the right plants for green roofs can be challenging. Plant species selection is heavily influenced by climate, microclimate, and environmental factors. The average low and high temperatures, severe cold and hot temperatures, irradiance level, wind speed, and the distribution and amount of rainfall throughout the year will all influence which species may thrive in each region (Arabi et al., 2015). Therefore, the chosen plants should be able to withstand the climatic conditions of their respective locations and geographical regions. It's preferable if these plants are native species (Monterusso et al., 2005). Vegetation helps to create sustainable urban settings by lowering temperatures through increased evapotranspiration and providing shade, so improving general comfort in cities. As a result, vegetation considerably reduces energy use for air conditioning in metropolitan areas, improving energy efficiency and cost-effectiveness (Zampieri et al., 2023). Numerous studies have been devoted to the selection of appropriate plants, and most of them agree that sedum species are excellent choices for extensive green roofs worldwide due to their adaptability to a variety of conditions. Scholars have reported that Sedum Rubrotinctum R. T. Clausen can endure a water-free environment for a duration of two years (Terri et al., 1986). Furthermore, after four months without water, the plant has maintained an active photosynthetic metabolism. Additionally, succulents are drought-resistant due to the water storage capacity of their stems and leaves (Shao et al., 2021).

The substance used in a plant container is referred to as the "growing medium." These mediums are typically crafted by blending different raw materials to achieve an optimal balance of air and water retention for plant growth (Jamei et al., 2023). As well as substrate layer functions are crucial for reducing water discharge and peak flow, enhancing water quality, and providing thermal benefits (Shao et al., 2021). Just like insulation features, factors such as the local climate and the thickness of the growing medium significantly influence the energy efficiency of green roofs (Jamei et al., 2023). A green roof growth substrate, like natural soil, provides physical support to plants while also supplying necessary plant nutrients (Ampim et al., 2010). The climate zone also influences the thermal performance of substrate, much like the vegetation on a green roof. Certain research indicates that in regions with cold climates, thermal efficacy is enhanced by a thick substrate as opposed to a thin substrate. In regions characterized by hot and humid climates, however, a 10 cm-thick, thin substrate is adequate to minimize the amount of energy needed to cool the space beneath (Pianella et al., 2017). (Sun et al., 2013) has been discovered that a deeper layer redistributes more water into the lower section, thereby preventing surface evaporation, whereas a shallow layer fails to store sufficient water, dries up rapidly, and degrades performance as well. This suggests that there is a layer thickness that is optimal to some degree intermediate.

Variations in soil moisture content result in different soil thermal performance, as water replaces the air within soil particles and fills the spaces between them (Shao et al., 2021). (Tsang and Jim, 2011) determined through an analytical model sensitivity analysis that a 30% increase in soil moisture content can result in a 24% reduction in the heat storage capacity of their green roof system. (Lin and Lin, 2011) discovered that irrigating twice a week in Kaohsiung, a subtropical location, enhances the thermal efficiency of their greenhouse. Due to the limited precipitation and the price of water and electricity, some researchers observed that the additional expenses of irrigation could outweigh the advantages of energy savings. Based on economic concerns and water scarcity, cities should investigate using gray water to irrigate green roof systems, according to their suggestions (Sun et al., 2013).

2.3.3 Case studies: Thermal performance of green roof compared to other roofs.

(Simmons et al., 2008) conducted research of thermal performance of green roofs compared with reflective(white) and non-reflective (black) roofs. Experimental setups were constructed in a former grazing field located in Austin, Texas, and the climate in this area is characterized as subhumid and subtropical, featuring a rainfall pattern that peaks twice a year. Researchers concluded that on a warm day with an ambient temperature of 33 °C, black roof membrane temperatures soared to 68 °C, while white roofs reached 42 °C in the afternoon. In comparison, green roofs maintained much cooler temperatures, ranging between 31–38 °C on their membranes. Inside, under black roofs, internal temperatures peaked at 54 °C, slightly lower at 50 °C under white roofs, whereas green roofs maintained internal temperatures between 36–38 °C. On a moderately warm day with a maximum ambient temperature of 27 °C on March 12th, black roof membrane temperatures reached a peak of 56 °C, white roofs at 32 °C, while green roofs stayed notably cooler between 22–27 °C. Inside temperatures were recorded at 45 °C and 40 °C for black and white roofs respectively, whereas green roofs kept internal temperatures between 27–29 °C. However, during cooler days with a maximum ambient temperature of 5 °C on April 7th, black and white roof membrane temperatures were notably cooler compared to green roofs, with differences ranging from 2–5 °C. Their findings indicated that green roofs maintained noticeably cooler internal structural temperatures on warm days compared to both traditional and cool roofs. However, there was no discernible difference in temperatures during the cold event among the three types of roofs.

Furthermore, (He et al., 2020) conducted a study that is a comparison between thermal performance of green roof and cool roof in Shanghai area. Shanghai, located in front of China's Yangtze River Delta, has four distinct seasons: hot and humid from June to September, cold and dry from December to March, and moderate spring and fall. Summer temperatures can reach over 40 °C, while winter temperatures can plunge around -5 °C. The daily average air temperature ranges from 25 °C to 31 °C in the summer and 4 °C to 10 °C in the winter. The study compared the thermal performance of green roofs, cool roofs, and traditional roofs in both summer and winter. The results revealed that in summer, the cool roof provided an average cooling effect of 3.3 °C on the outer surface of the roof deck compared to the common roof, while the green roof's cooling effect was slightly lower at 2.9 °C. However, in winter, the green roof exhibited good insulation properties, improving the outer surface temperature of the roof deck by an average of 3.3 °C compared to the cool roof.

2.3.4 Thermal performance of green roofs in various climates.

The effectiveness of green roofs in reducing heat transfer and energy consumption depends on various factors like insulation, substrate, irrigation, and vegetation. However, their performance is greatly influenced by the local climate conditions (Jamei et al., 2023). In tropical areas, where buildings face substantial thermal challenges, research indicates that air conditioning accounts for a significant portion of electricity consumption (IEA, 2018). Specifically, in Singapore, it can be up to 40-50%, in Hong Kong around 40%, and in Taiwan approximately 28%. A primary contributor to the building's thermal burden is the heat absorbed through the roof (Zingre et al., 2014). Researchers investigated the passive cooling impact of green roofs in the humid, tropical climate of Hong Kong. They studied three vegetated areas: one with grass, another with groundcover herbs, and a third with shrubs, each with different growth forms and biomass structures. They also included a bare control plot for comparison (Jim, 2011). The research contributed to grasp how three types of vegetation affect air, surface, and substrate temperatures at seven different levels in a humid, tropical setting. At night, the green roofs don't cool the air more than the control roofs do. Among the vegetation types, grass provides more air cooling compared to groundcover and shrubs. During daytime, grass creates a small, suspended temperature inversion, while shrubs create a canopy temperature inversion (Jim, 2011). As well as (Wong et al., 2003) investigated the direct and indirect thermal impacts of rooftop garden under tropical climate. The study summarized that the presence of plants was found to have a cooling effect, as observed through the ambient air temperatures recorded at various heights. A maximum temperature difference of 4.2 °C was noted between areas with and without plants and due to the shading provided by plants, surface temperatures measured beneath various types of vegetation were significantly cooler compared to those measured on hard surfaces. The maximum temperature contrast between shaded soil and hard surfaces was approximately 30 °C. The temperature recorded beneath the vegetation depended on the density of the plants, also known as LAI. Finally, (Hien et al., 2007) studied thermal performance of extensive rooftop greenery systems in the tropical climate. The research was conducted in Singapore and A greatest temperature difference of 18 °C was measured. When the substrate is exceptionally dry, the recorded temperature can be higher than the surface temperature of the original exposed roof. The installation of extensive systems significantly reduced heat flux through the roof structure. The system effectively prevented more than 60% of heat gain. The impact of various vegetation kinds may also differ. Those with somewhat substantial vegetation coverage have superior thermal performance.

(Bevilacqua et al., 2016) investigated the thermal performances of an extensive green roof in the Mediterranean area. The analysis revealed that during summer, green roofs can lower the temperature at the interface with the structural roof by an average of 12 °C compared to a black bituminous roof. In winter, they maintain a temperature approximately 4 °C higher on average. By measuring these temperatures, researchers were able to calculate the heat transferred through the building roof, showing negative heat fluxes throughout the study period. This resulted in a complete reduction of thermal energy entering the indoor environment during summer, demonstrating the passive cooling effect of green roofs. Additionally, in winter, there was a reduction of between 30% and 37% of thermal energy exiting the indoor environment. Other practical experiments have been undertaken under Mediterranean climate conditions. (Coma et al., 2015) conducted a study in Puigverd de Lleida, Spain, where they evaluated the energy consumption and thermal performance of three similar house-like structures. Two of these structures had extensive green roof systems installed with different drainage layer materials (pozzolana and rubber crumbs) on a traditional uninsulated flat roof, while the third had a conventional insulated roof. They monitored the electrical energy consumption of a heat pump system for over a year. Their findings revealed that during warm periods, both cubicles with extensive green roofs consumed less energy (16,7% and 2,2% less, respectively) compared to the reference cubicle with a conventional insulated roof. However, during heating periods, they observed higher energy consumption (6,1% and 11,1% more, respectively) in the cubicles with extensive green roofs.

Toronto, the largest municipality in Canada, faces environmental concerns such as poor air quality, UHI effects, and stormwater management issues like many other cities. The city experiences a continental climate, which is notably influenced by its proximity to the Great Lakes (McGillivray and Howarth, 2024). In 2009, Toronto made history by becoming the first city in North America to implement a bylaw mandating and regulating the construction of green roofs. Known as the

Green Roof Bylaw, it establishes a progressive mandate for new developments or expansions exceeding 2 000 m^2 in gross floor area (Mahmoodzadeh et al, 2019) (Toronto, 2022). This regulation requires that a portion of the Available Roof Space of a building must be allocated to green roofs, with the requirement varying between 20% and 60%. Toronto Building, in collaboration with the City's Green Roof Technical Advisory Group, developed a guideline document outlining green roof building standards. It includes optimal design techniques, insights into the Toronto Green Roof Construction Standard, and graphics to help determine required green roof coverage (Toronto, 2022). (Liu et al., 2005) The research shows that green roofs are beneficial for reducing heat transfer through the roof, which ultimately decreases the energy needed to maintain comfortable indoor temperatures in buildings, regardless of the type of roofing system. These green roofs are particularly effective during the summer months compared to winter. For instance, lightweight extensive green roofs with 75-100 mm of growing medium significantly decreased heat flow through the roof by 70-90% in summer but only by 10-30% in winter.

3. Materials and Method

For the purpose of analyzing the thermal performance of green roofs and comparing them with shingle roofs, we set up three model houses on the campus of the university. During the summer of 2023, we used temperature data loggers to measure both interior and exterior temperatures of the model houses at intervals of five minutes. Moreover, the temperatures of the east and west sides of the model houses are measured separately. Perennial Ryegrass was used in green roof.

3.1 Experimental site.

Gödöllő (47.6008° N, 19.3605° E) is a city in Pest County, Budapest metropolitan area in Hungary, Europe. The Hungarian University of Agriculture and Life Sciences campus was the location where the thermal performance of green roofs was measured and compared to that of shingle roofs.

Gödöllő, Hungary, located in Central Europe, has a Köppen climatic classification of CFA which is a humid subtropical climate zone, signifying a marine west coast environment with a warm summer. The yearly weather pattern in this area shows a distinct contrast between the warmer and colder months, with notable fluctuations in temperature and precipitation levels.

The warm season lasts 3,6 months, beginning on May 23rd and ending on September 11th. During this time, the average daily high temperature reaches 22 °C. In Gödöllő, July has the greatest temperatures of the year, with an average high of 26 °C and a low of 15 °C. In contrast, the winter season lasts 3,4 months, beginning on November 20th and ending March 1st. During this time, the average daily high temperature is below 6 °C. The coldest month in Gödöllő is January, with an average low of -4 °C and a high of 2 °C.

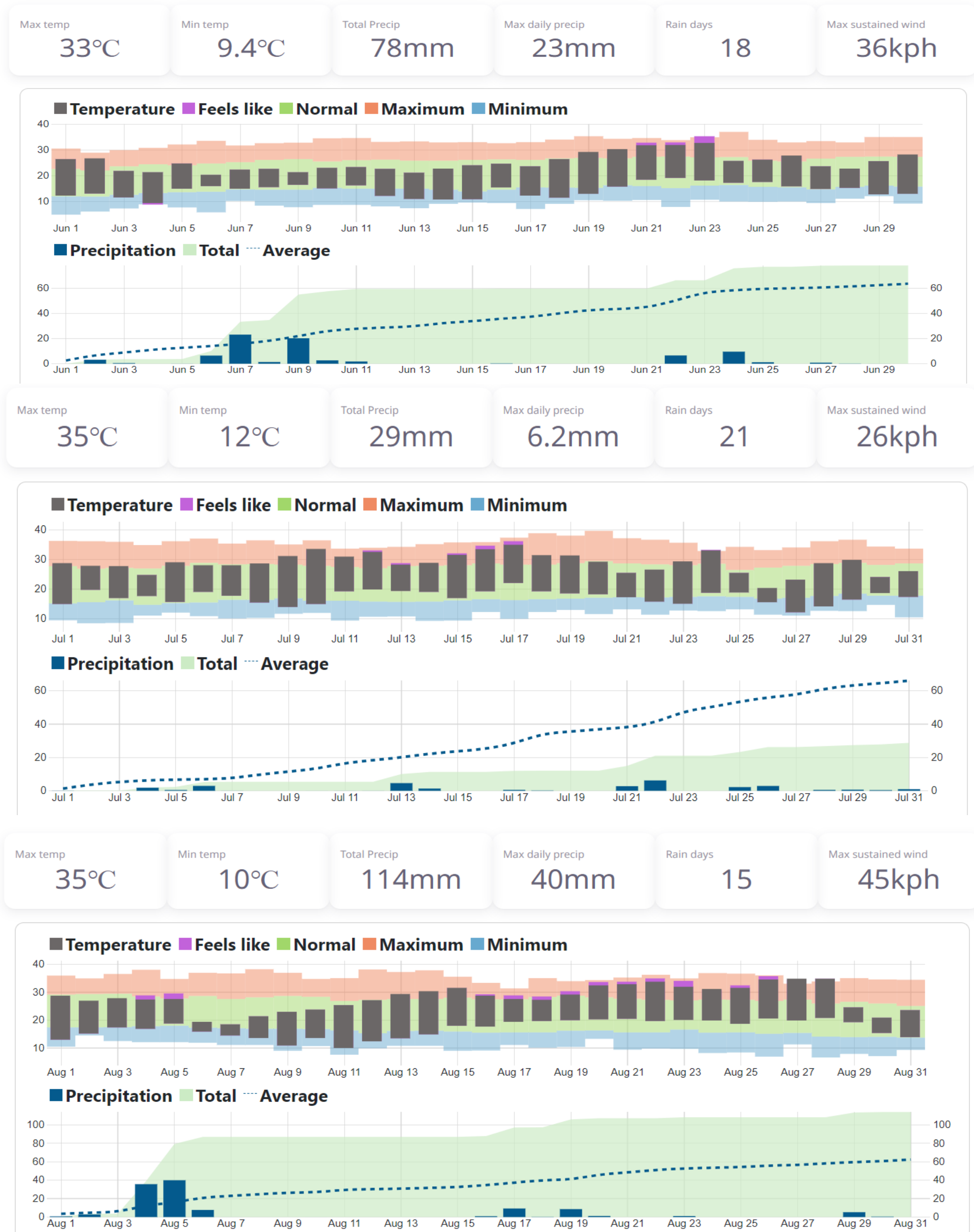

Figure 6. Weather data of Gödöllő in Hungary during summer of 2023 (Visual Crossing: Weather Data & Weather API, 2023).

3.2 Model houses

To assess the thermal performance of green roofs, we've set up three model houses, each with a distinct roofing system. There is a house with a green roof, a house with solar panels on the roof, and lastly a house with regular shingle roofing. This diverse setup allows us to compare and

Figure 7. Model houses.

analyze how these different roofing materials impact the thermal behavior of the houses. For my thesis work, I focused only on comparing the thermal performance of green roofs versus shingle roofs. Therefore, within our setup, we installed two model houses: one with a green roof and the other with a shingle roof. The inclusion of a model house with solar panels on the roof was part of my colleague's separate analysis project. This ensured that our research remained focused on examining the specific differences between green and shingle roofing in terms of thermal efficiency.

As Figure 8 shows, the model houses are made up of several essential components that were chosen with careful consideration for their functionality. Firstly, expanded polystyrene (EPS) is used in the construction of the exterior wall, which acts as an efficient insulating barrier against fluctuations. In the interior, the wall material is made of Ytong, which was selected due to its durability and insulation properties. PVC pipes are carefully installed between the walls of the construction to provide stability and support and fix the structure. Planks made of wood are added into the house. These planks not only give weight and solidity to the structure, but they also provide protection from severe winds. Additionally, a waterproof membrane is applied to the roof's surface.

Our objective was to create a small scale of house that resembles real-life structures as close as possible to obtain precise results. The dimensions of both model houses were 80cm x 110cm x 70cm.

Figure 8. a) Dimensions of model house. b) Interior components of model houses.

The vertical distance between the two roofs was 180cm, while the horizontal distance was 100cm.

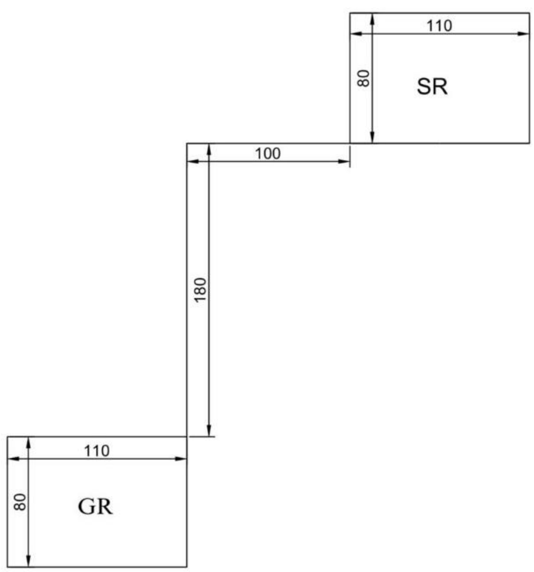

Figure 9. Green roof and Shingle roof's 2D schematic location. Dimensions in cm.

The roof shapes of the houses are called gable roofs and the side of the roofs face east and west. The green roof element comprises an extensive green roof with a substrate depth of 3.5cm and the vegetation type is Perennial Ryegrass. Its dimensions for greening are 90cm x 110cm. The roof area is 10120 cm^2, whereas the greening area is 9900 cm^2.

Beneath the green roof, there's a drainage layer installed, along with a metallic component that for waterproofing and held up the green roof structure. On the other hand, we installed shingle material on the roof, placing it over a waterproof membrane made of plastic.

Figure 10. Green roof and Shingle roof model houses.

3.3 Experimental green roof and conventional roof

The most important piece of equipment in the model houses was the data logger, the Ebro EBI 300 TE (Germany), which is a multi-use USB data logger with an external temperature probe and a battery-powered temperature measurement and recording instrument. The external sensor recorded the interior temperature of model houses, while the internal sensor recorded the exterior temperature of the model houses. The temperature reading range of the internal sensor is minimum of -30 °C and maximum of 70 °C and the external probe ranges from minimum of -35 °C and maximum of 75 °C. It has an accuracy of ±0,5 °C within the temperature range of -20 °C to 40 °C, and an accuracy of ±0.8 °C for temperatures outside of this range.

The sensors' type is negative temperature coefficient (NTC). The external probe has a diameter of 4 mm, a length of 50 mm, and is made of stainless steel. The cable that connects to the probe has a length of 100 cm and is waterproof and oilproof.

Figure 11. Ebro EBI 300 TE temperature data logger.

We used two temperature data loggers in a single model house to measure the temperature on both east and west sides of the roofs. The data logger gathered temperatures at five-minute intervals and on a biweekly basis during the summer period June to September. The data was gathered utilizing the Winlog.basic software program. Furthermore, the green roof was irrigated once a week during the measurement periods in addition to precipitation.

The temperature data obtained from the Winlog.basic software program was successfully imported into Microsoft Excel for detailed analysis. By using the powerful functionalities of Excel, various tools and functions were employed to conduct a comprehensive comparison of the thermal performance between the green roof and the shingle roof.

Excel's important features enabled the organization and manipulation of the temperature data, allowing for easy visualization and interpretation of trends. Utilizing functions such as AVERAGE, MIN, MAX, and SUM, statistical analyses were performed to calculate key metrics such as average temperatures, temperature differentials over specific time periods. In addition, Excel's conditional formatting and data validation features were used to emphasize temperature anomalies or outliers, guaranteeing the precision and dependability of the analysis findings.

To calculate the temperature differences of model houses, we subtracted the temperatures of the green roof from the temperatures of the shingle roof.

4. Results

The results of field application were analyzed by comparing internal and external temperatures of both sides of each roof during the measurement periods from June to September. The charts of temperature comparisons are shown at intervals of 600.

Table 1. Strategy for conducting a systematic comparative analysis of green roof and shingle roof.

Comparative analysis	
Interior temperature of the green roof' on the east side (GEI)	Interior temperature of the shingle roof on the east side (SEI)
Exterior temperature of the green roof on the east side (GEE)	Exterior temperature of the shingle roof on the east side (SEE)
Interior temperature of the green roof on the west side (GWI)	Interior temperature of the shingle roof on the west side (SWI)
Exterior temperature of the green roof on the west side (GWE)	Exterior temperature of the shingle roof on the west side (SWE)

Figure 12 displays the thermal performance of GEI and SEI throughout the summer of 2023. It was found that the difference in thermal performance of GEI and SEI ranges between -0,5 and 6,3 °C while average temperature difference shows approximately 1,3 °C. The measurements indicate that from approximately 10 PM to 10 AM the following morning, the temperature contrast between the interior environments of the green roof and shingle roof fluctuates between -0,1 to -0,5 °C on the east side. However, after 10 AM, the difference begins to show positive value. The fluctuations in temperature suggest that during the daytime, the green roof functions as a heat sink, absorbing and retaining heat. Conversely, at night, it behaves as a heat source, emitting heat absorbed during the day. A maximum temperature of 33,3 °C was obtained by the inner green roof on the east side, while the interior shingle roof reached 35,3 °C. However, it is important to mention that the lowest temperature recorded for the GEI was 15,5 °C, whereas the minimum temperature observed for the SEI was 16,7 °C. When the temperature on the SEI climbs above 33 °C, the temperatures of GEI are constantly lower than SEI by a range of 0,8 to 3,9 °C.

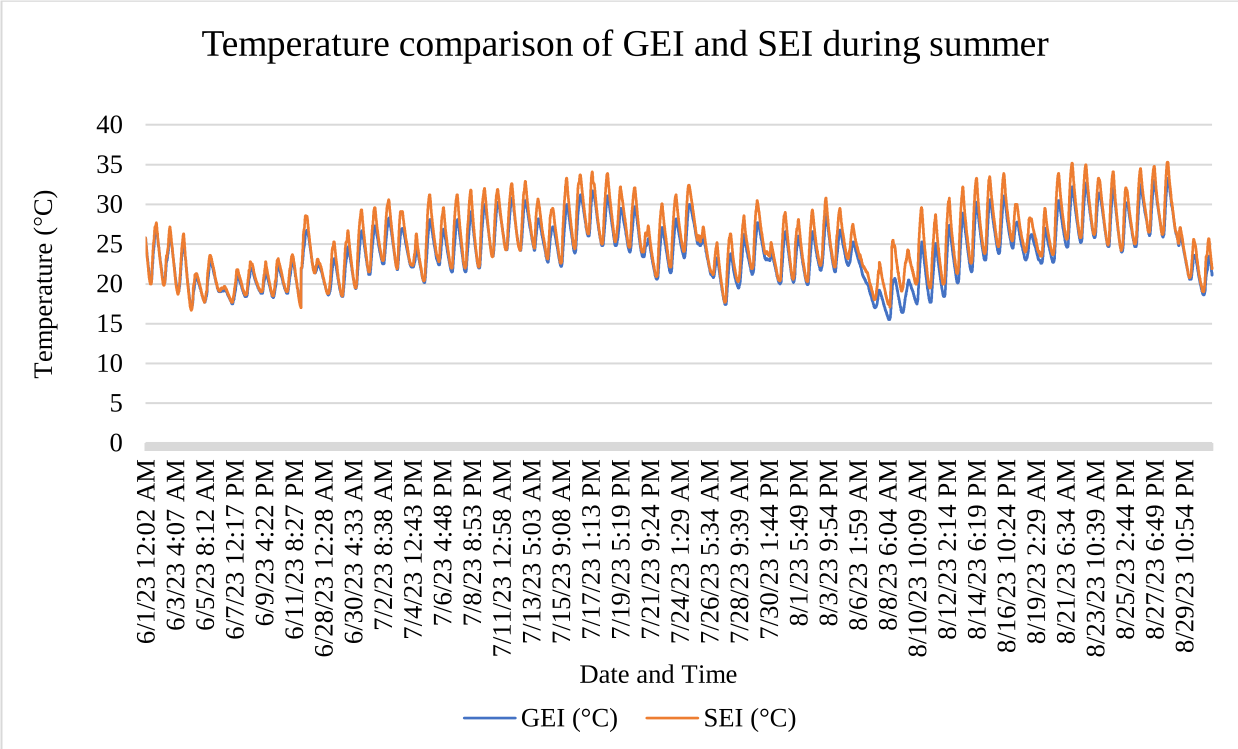

Figure 12. Comparison of GEI and SEI.

According to Figure 13, the GWI and SWI achieved maximum temperatures of 35,7 °C and 35,6 °C degrees, respectively, and minimum temperatures of 17,1 °C and 15,4 °C. In addition, the temperature difference varies between -3,1 °C and 4,4 °C. From June to mid-July, there was no notable change in the temperature differences between the roofs. However, starting on July 18th, the temperature of GWI frequently registered lower readings, ranging from 0,3 to 3 °C, compared to SSI between 11 AM to 5 PM, especially when interior temperatures of both roofs exceeded 25 °C. Additionally, we saw a consistent trend where the temperature of the green roof is generally greater than that of the shingle roof between the hours of around 5 PM and 11 AM the following morning. During August, the temperature difference was greater than in July, ranging from 1 to 3 °C during the same hours.

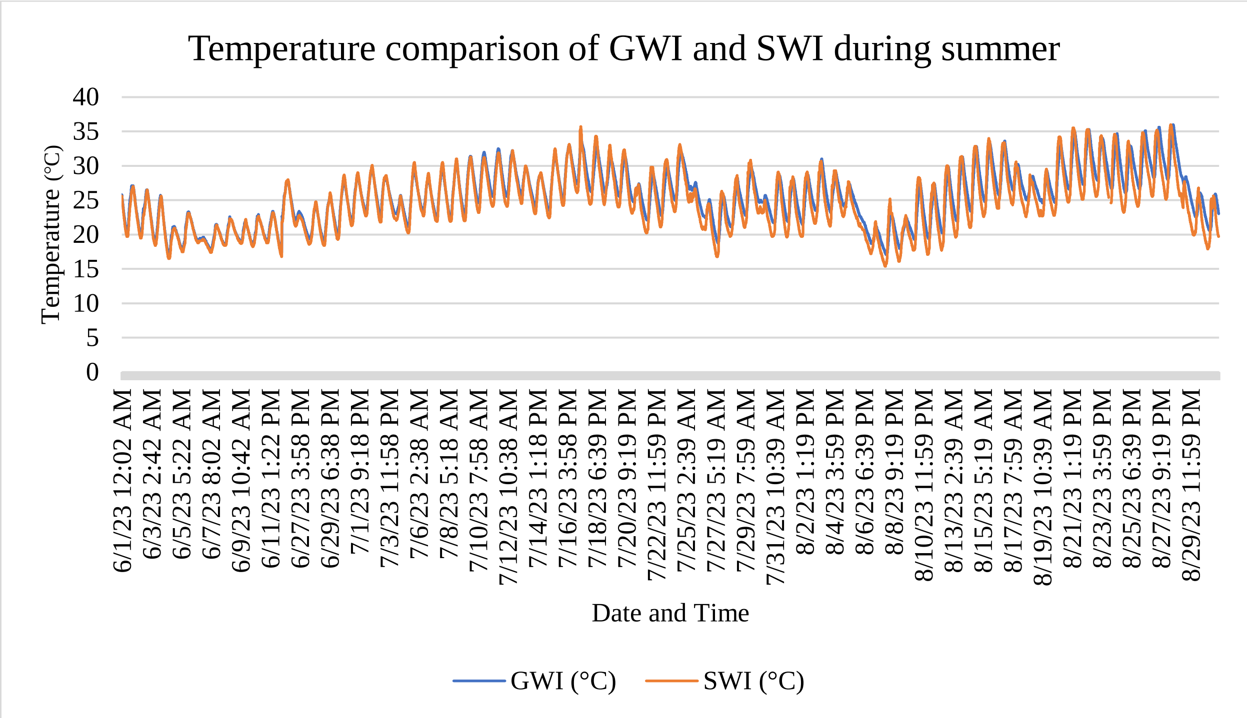

Figure 13. Comparison of GWI and SWI.

According to Figure 14, the most significant temperature difference recorded was 20,7 °C, occurring on June 29th at 5:58 pm. This gap occurred when GEE's temperature measured 28,6 °C, while SEE's temperature reached 49,3 °C. Additionally, on that day, we observed temperature gaps of 20,5 °C and 19,8 °C. The maximum temperatures recorded in GEE and SEE were 53,7 °C and 51 °C, respectively while lowest temperature reached to 8,2 °C and 8 °C.

During the period from June 26th to July 12th, the thermal performance of the green roof undergoes significant hourly fluctuations. The observed pattern indicates that between 3:30 pm and 4:30 pm, the exterior temperature of the green roof on the east side was consistently higher than that of the shingle roofs, with a maximum difference of 9 °C. Between 5:30 AM and 6:30 PM, the green roof exhibited a significant cooling effect, reducing the temperature by a maximum of 15,4 °C. Additionally, between 6:30 AM and 7:30 PM, the shingle roof had a lower temperature than the green roof, with a maximum difference of 10,2 °C. However, for whatever reason, the temperature of the green roof was greater than the shingle roof between 6 AM and 9 PM on July 13th and August 10th by a maximum of 21,4 °C. During the remaining hours, the temperature of the green roof was lower compared to the shingle roof.

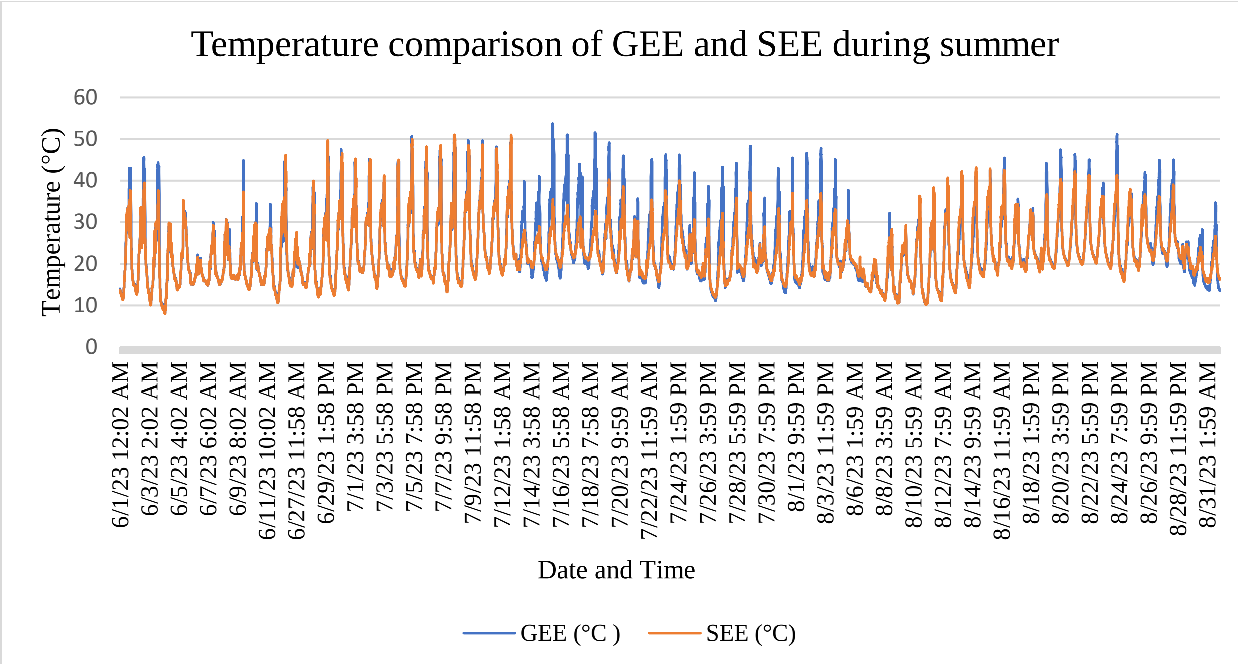

Figure 14. Comparison of GEE and SEE.

When comparing temperatures between GWE and SWE, we observed that the green roof had the maximum efficiency, with a temperature of 28,6 °C lower than the shingle roof on the day of August 24th at 10:24 AM. The maximum temperatures recorded in GWE and SWE were 54,6 °C and 58,7 °C, respectively while lowest temperature reached to 8,2 °C and 8 °C.

As Figure 15 shows, Between July 5th and July 16th, the green roof's exterior temperature on the west side was drastically higher than the shingle roof, especially during the hottest periods of a day which from 9 AM till 6 PM. The temperature difference reaches maximum of 15,4 °C. Conversely, from July 16th to August 7th, the temperature of the green roof was significantly lower than the shingle roof, with a maximum difference of 15,4 °C between 10 AM and 5 PM. Additionally, from July 6th to August 15th, the temperature of the green roof was consistently lower throughout the cooler hours of a day, specifically between 9 PM and 8 AM, by a maximum of 2,2 °C.

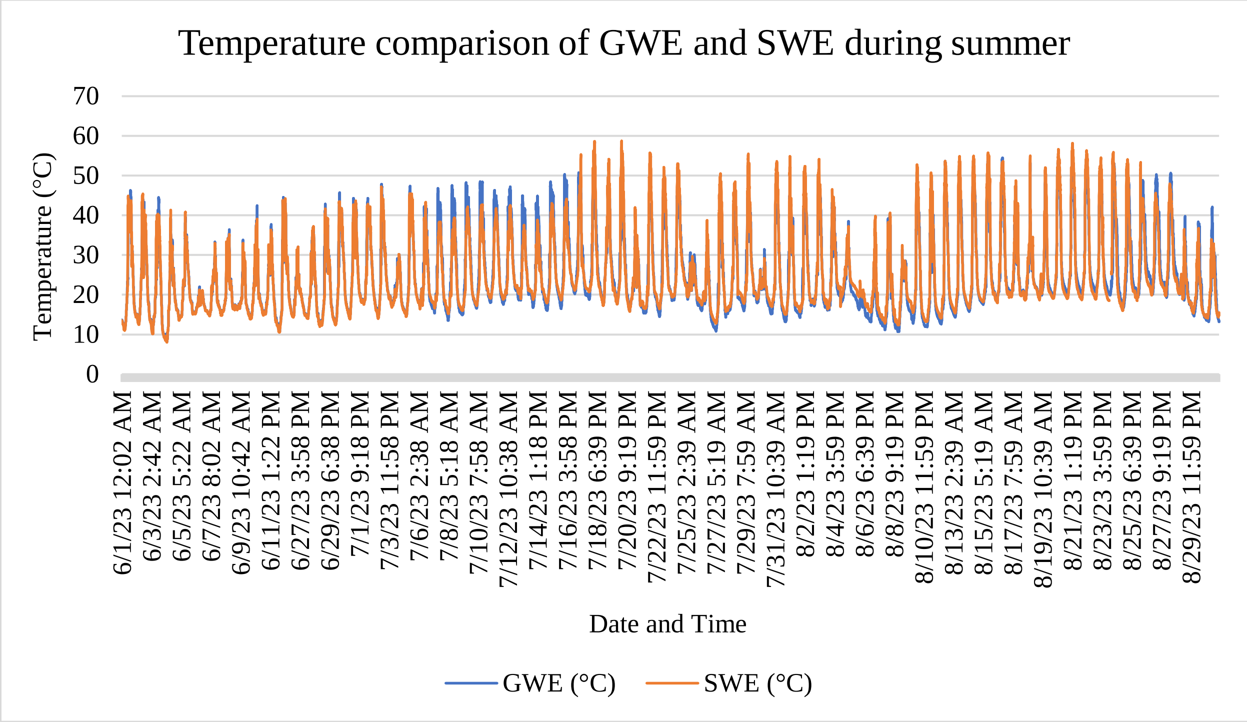

Figure 15. Comparison of GWE and SWE.

We randomly select a day on August 25th to thoroughly analyze the differences between the model houses. As Figure 16 shows the temperatures of GWE and SWE, from approximately 10 PM to 7 AM, there was no significant distinction between the thermal performance of the green roof and the shingle roof. Starting at 9 AM, the temperature differences gradually increased throughout the hottest period of the day until 1 PM. The green roof was both delaying and decreasing heat simultaneously. However, starting from 1 PM, the green roof began to experience higher temperatures than the shingle roof as it released the accumulated heat. The greatest temperature recorded for GWE was 48,2 °C, while SWE achieved a temperature of 54 °C at 1:54 PM and 11:49 AM, respectively.

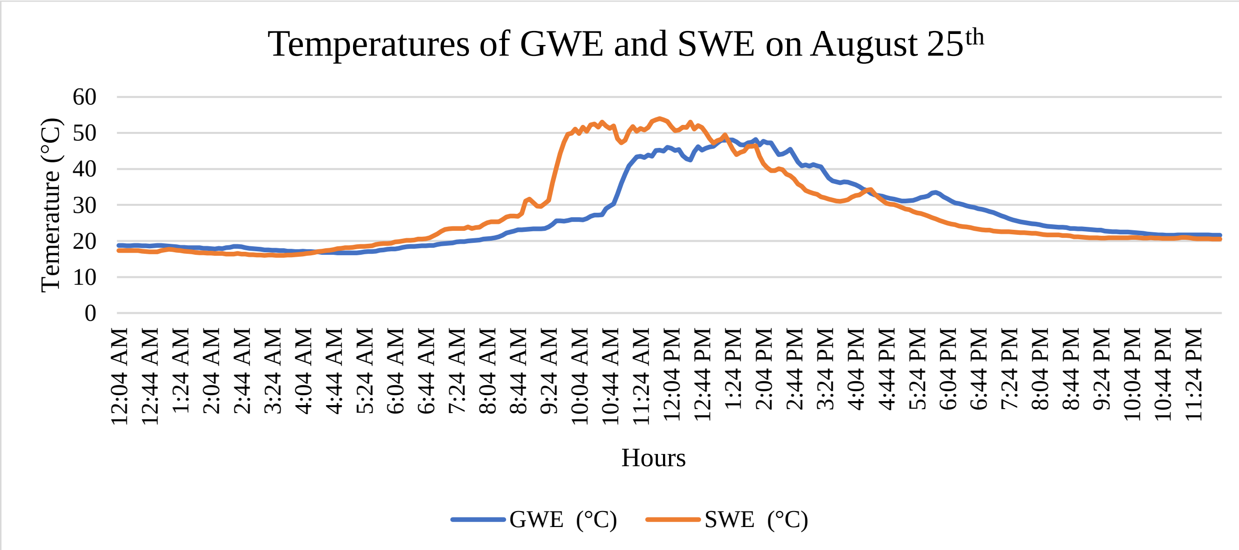

Figure 16. Temperatures comparison of GWE and SWE on August 25th.

Furthermore, in terms of GEE and SEE, there was no significant temperature difference between the roofs, like GWE and SWE. The temperature of the green roof was slightly lower than the shingle roof during daytime with the maximum temperature difference of 3 °C occurred at 12:04 PM.

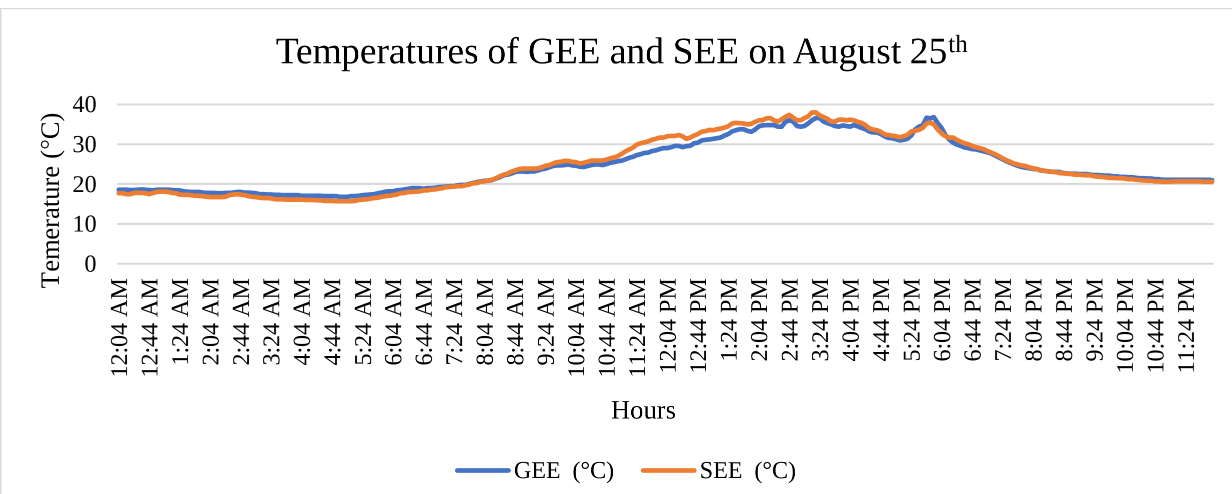

Figure 17. Temperatures comparison of GEE and SEE on August 25th.

We observed that the interior temperature of the model houses remained more consistent compared to the fluctuations in the external environment in Figure 18. During the peak hours of 10 AM to 3

PM, we found that the green roof outperformed the shingle roof in terms of thermal performance. The temperature of the GWI was lower than the SWI with maximum of 4,5 °C at 11:59 AM. However, over the remaining hours, the SWI shows temperatures that are 4.3 °C lower than the GWI.

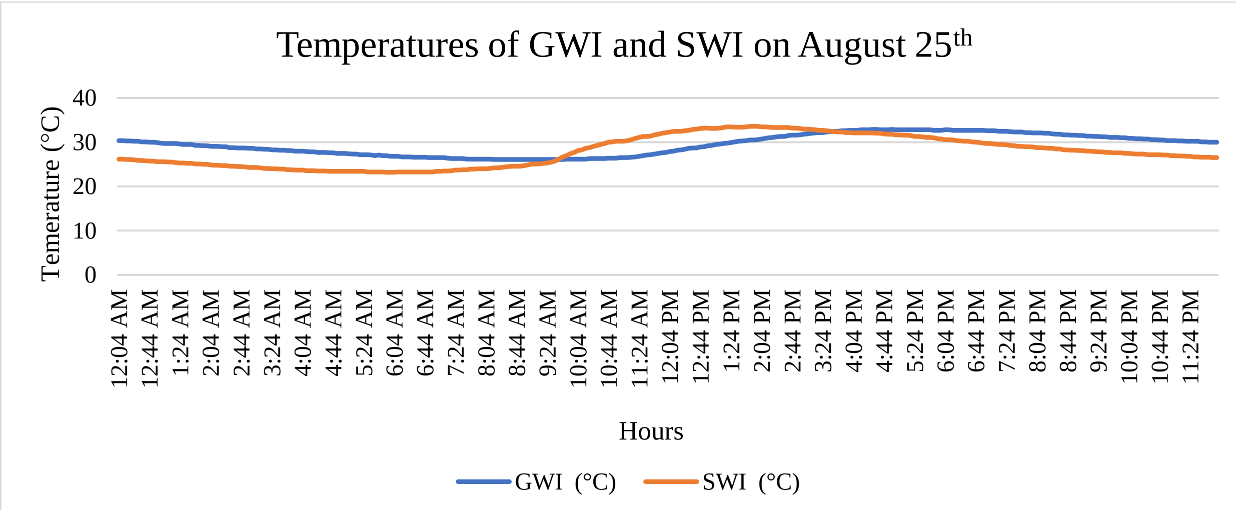

Figure 18. Temperatures comparison of GWI and SWI on August 25th.

As Figure 19 demonstrates, the temperatures of GEI and SEI were quite similar to each other except the time period of 11:30 PM to 8 PM, GEI gained less heat than SEI by maximum temperature of 2,5 °C.

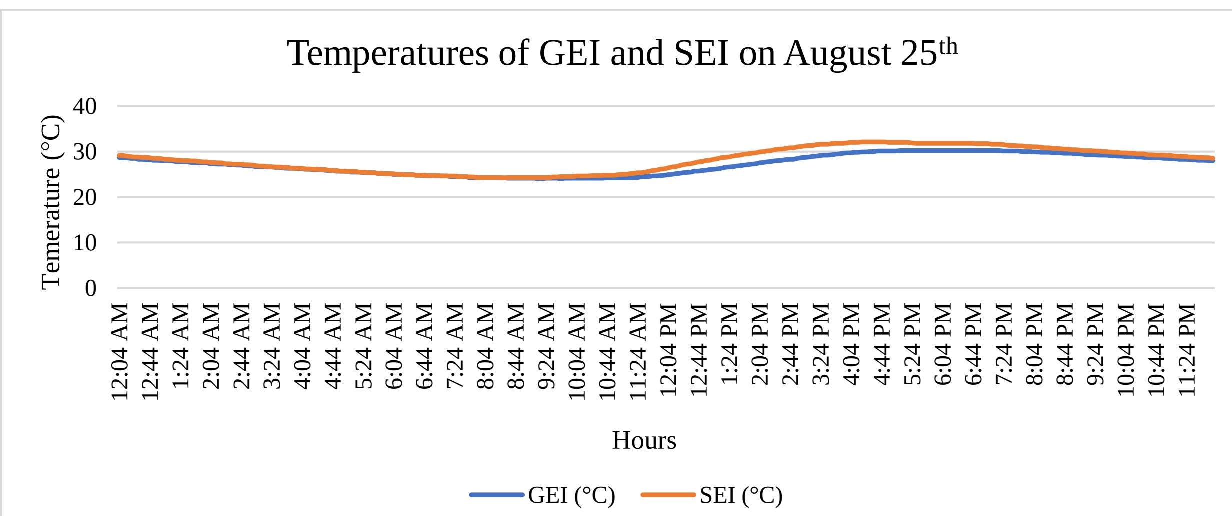

Figure 19. Temperatures comparison of GWE and SWE on August 25th.

Figure 20 shows the temperature of GWI from July 10th to July 16th. The temperature trends throughout the week indicate a consistent fluctuation between 23,5 °C and 33 °C.

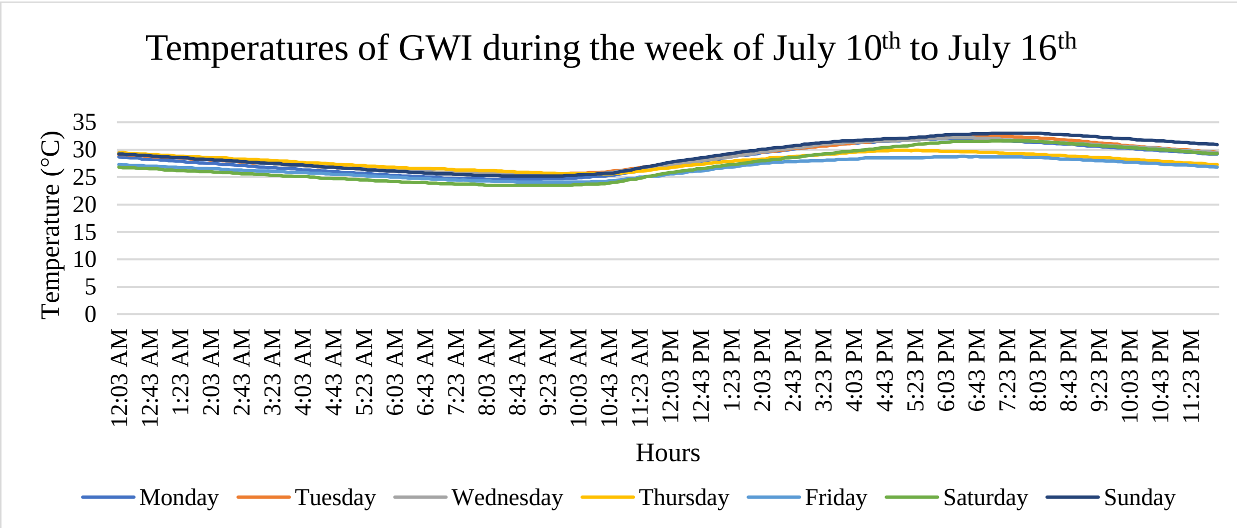

Figure 20. Temperatures of GWI during selected week of July 10th to July 16th.

In contrast, the temperature trends of SWI were fluctuating between 22,4 °C and 33,1 °C.

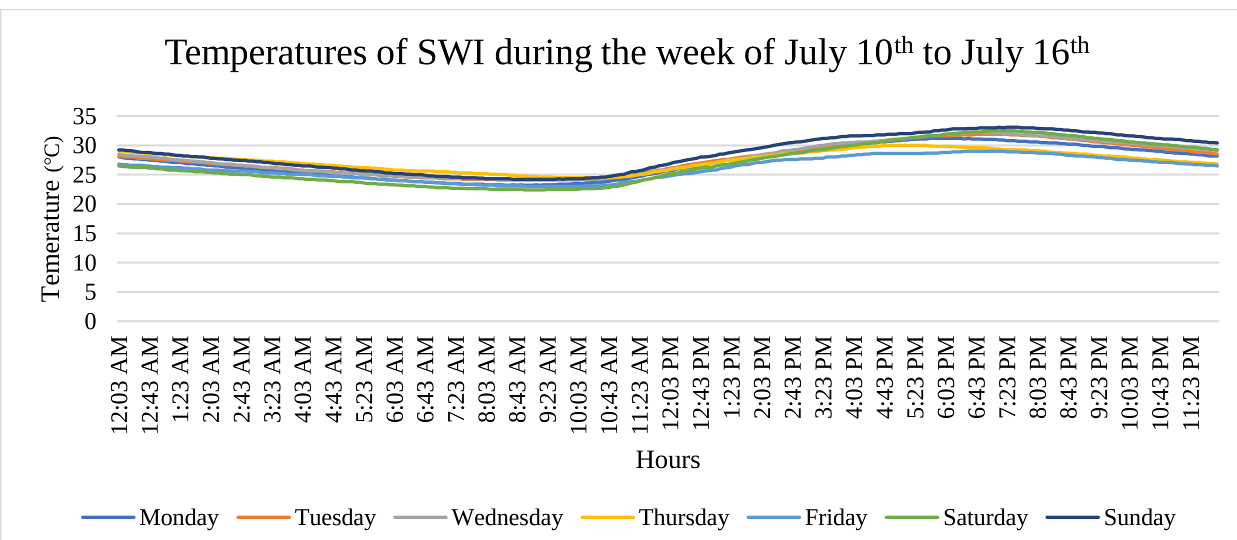

Figure 21. Temperatures of SWI during selected week of July 10th to July 16th.

Figure 22 shows the temperature of GEI from August 7th to August 13th. The temperature trends throughout the week indicate a fluctuation between 17,1 °C and 32,2 °C. The temperature fluctuation of SEI is higher than GEI.

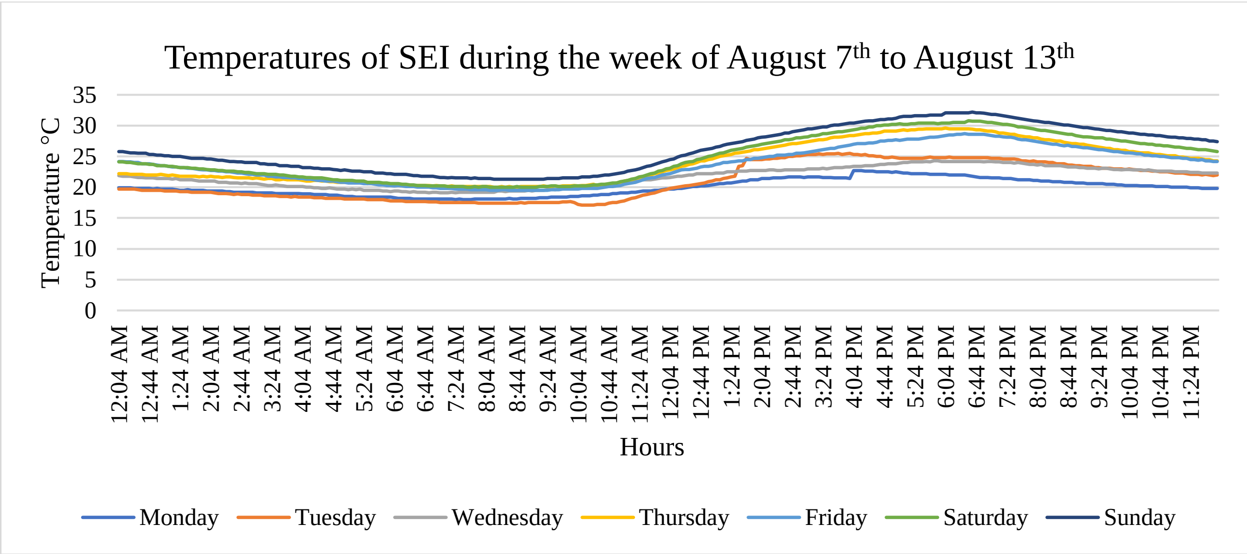

Figure 22. Temperatures of SEI during selected week of August 7th to August 13th.

On the other hand, the temperature trends of GEI were ranging from 16,4 °C to 28,9 °C.

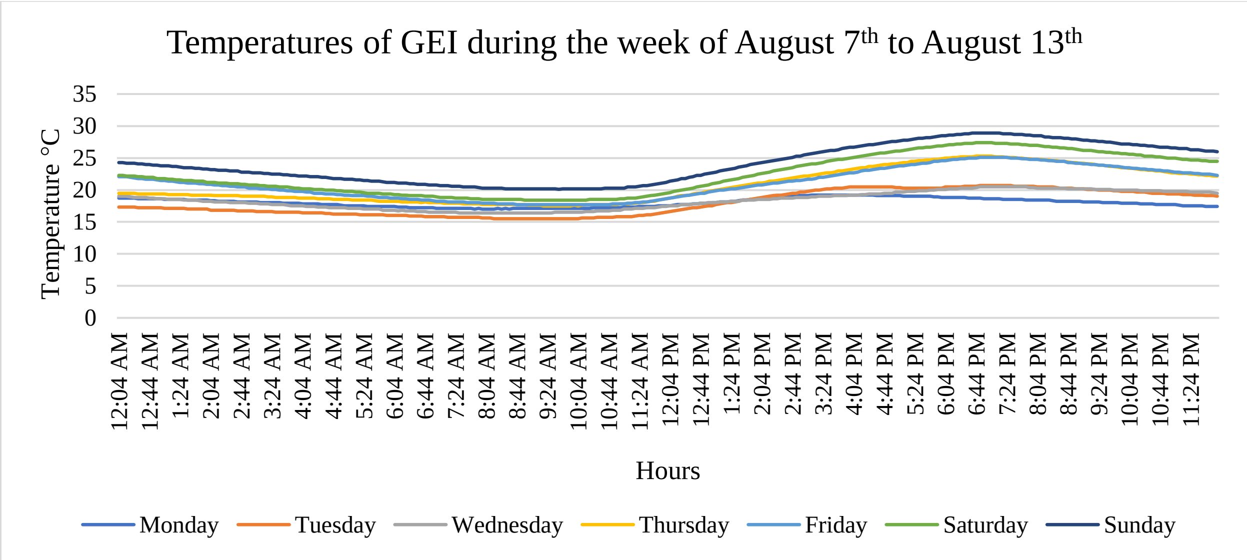

Figure 23. Temperatures of GEI during selected week of August 7th to August 13th.

5. Conclusion

This thesis focused on comparing the performance of green roofs and shingle roofs within buildings. We analyzed their performance both inside and outside the houses and evaluated their effectiveness on the east and west sides of the roof. This involved a detailed investigation of how these roofing materials affect temperature regulation and environmental consequences. The comparison between GEI and SEI, GWI and SWI, GEE and SEE, and GWE and SWE provides comprehensive insights into the thermal performance of both roof types during the summer of 2023.

Based on the results of the measurements, it is certain that the west sides of both the interior and exterior temperatures of the roofs showed greater values than their respective east sides. This observation indicates a regular pattern where the western side receives a greater amount of direct sunlight and heat, leading to higher temperatures inside the building and on the roofs' exterior surfaces. The findings confirm that the thermal performance of gable roofs is influenced by their orientation, mostly as a result of solar radiation.

Between 10 AM and 5 PM, which are the peak hours of sunlight, GEI, GWI and GWE roofs acted as heat sinks, effectively reducing heat. However, an exception was observed with GEE, which consistently maintained higher temperatures than SEE during the middle of the summer. While we cannot provide an explanation, it is possible that surrounding shading played a role in this phenomenon.

In the results section, August 25th was selected as a representative day for detailed temperature analysis. The observations revealed that the west sides of both roofs exhibited greater temperature fluctuations compared to the east sides. This indicates that the western orientations experienced more significant variations in temperature throughout the day. The chosen representative day further confirms the overall pattern that temperatures on the western side of the roofs consistently exceed those on the eastern side. Furthermore, it shows that during the peak heat hours of the day, both the east and west sides of the interior and exterior temperatures of the green roof were notably lower compared to those of the shingle roof.

Finally, a random week was selected for GWI and SWI from July 10th to July 16th, whereas GEI and SEI were assigned to another week from August 7th to August 13th. The pairs were individually analyzed for a certain week. The analysis revealed that green roofs have an important effect on minimizing temperature fluctuations and ensuring consistent temperatures.

Overall, green roofs serve as natural regulators, effectively moderating temperature fluctuations. They enhance the insulation and cooling effects, resulting in a more consistent and comfortable environment, whether you're inside or outside. This discovery highlights the significance of green roofs in not just reducing the effects of extreme weather, but also in supporting sustainability and improving the quality of urban living areas.

6. Summary

Rapid urbanization and economic expansion have reduced green spaces in cities and increased pollution, contributing to global warming. Green roofs are widely recognized as a highly effective solution for enhancing the indoor and outdoor environment in both buildings and metropolitan areas. Green roofs offer numerous advantages when compared to traditional roofs. These include lowering the temperature of the roof and surrounding air, reducing air pollution, improving water runoff management, enhancing urban biodiversity, minimizing noise, and decreasing energy consumption in buildings, particularly for cooling.

In this thesis, I explored how green roofs can contribute to urban development by mitigating solar radiation towards buildings. By comparing temperatures between green roofs and traditional shingle roofs, I aimed to uncover their effectiveness in reducing heat, focusing on both the east and west orientation of the roofs as well as interior and exterior temperatures. The study took place at the campus of the Hungarian University of Agriculture and Life Science in Gödöllő, Hungary.

Between June 1st and August 31st, 2023, temperature data was collected at 5-minute intervals from both green roof and traditional shingle roof model houses. The roof type of the model houses was gable roof which has two sloping sides. For each model house, two temperature data loggers were installed on the east and west sides of a roof. Additionally, a single temperature data logger was used to measure both the interior and exterior temperatures of the model houses using an EBI 300 data logger. Microsoft Excel software program was used for advanced data analysis.

The study's findings emphasize the significant effect of roof orientation on thermal performance, as the west sides of the roofs frequently demonstrate higher temperatures due to greater solar radiation exposure. With the exception of the exterior temperature on the east sides of the green roof (GEE), all other temperature readings of green roof functioned as heat sinks between the peak sunlight hours of 10 AM and 5 PM. GEE sustained higher temperatures, potentially as a result of shading in its surroundings. A detailed analysis conducted on the day of August 25th, selected randomly, confirmed the constant trend of elevated temperatures on the western side. Moreover, during this peak heat period, both the east and west sides of the green roof demonstrated notably lower temperatures compared to the shingle roof.

The analysis of randomly selected weeks highlighted the positive impact of green roofs in minimizing temperature fluctuations and maintaining consistent temperatures. Overall, green roofs emerged as natural regulators, enhancing insulation and cooling effects to create a more comfortable and sustainable urban environment. This discovery exposes the importance of green roofs in mitigating extreme weather effects and improving the quality of urban living spaces.

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