Czech University of Life Sciences Prague

Faculty of Environmental Sciences
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(FZP)

Master's Thesis

Mitigating Urban Heat Islands through Green Roofs in High-Density Cities (case study: Cairo as an example)

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DIPLOMA THESIS ASSIGNMENT

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Landscape Engineering
Landscape Planning

Thesis title

Mitigating Urban Heat Islands through Green Roofs in High-Density Cities (case study: Cairo as an example)

Objectives of thesis

Urbanization has led to the rapid expansion of high-density cities, resulting in various environmental challenges, with urban heat islands (UHIs) being one of the most concerning issues. UHIs are characterized by higher temperatures in urban areas compared to their surrounding rural regions, primarily caused by the replacement of natural surfaces with impervious materials, reduced vegetation, and increased heat-generating activities. Mitigating UHIs is crucial for enhancing urban livability, reducing energy consumption, and promoting overall environmental sustainability. This thesis aims to explore the potential of green roofs, living walls, and biophilic architecture as strategies to mitigate UHIs in high-density cities such as Cairo nowadays after the deforestation that is currently happening due to construction and expanding the roads network.

1. To examine the causes and impacts of urban heat islands in high-density cities.
2. To assess the effectiveness of green roofs and living walls in reducing surface temperatures and mitigating UHIs.
3. To investigate the influence of biophilic architecture on urban microclimates and human comfort.
4. To analyze the feasibility and challenges of implementing these strategies in various high-density urban contexts.

Methodology

1. Data Collection: Data collection will involve gathering historical temperature records, land cover data, and urban development patterns to identify UHI trends and hotspots in selected high-density cities.

2. Case Studies: Case studies of cities that have successfully implemented green roofs, living walls, and biophilic architecture will be conducted to analyze the strategies' effectiveness and challenges.

3. Microclimate Analysis: Microclimate simulations using modeling tools will be employed to assess the impact of green roofs, living walls, and biophilic architectural features on temperature reduction and local climate conditions.

Expected Outcomes:

1. Quantitative Data: The research is expected to generate quantitative data on temperature reductions achieved through the implementation of green roofs, living walls, and biophilic architecture.

2. Design Guidelines: The study will propose design guidelines for integrating these strategies into the urban fabric, accounting for different architectural typologies and contextual factors.

3. Policy Recommendations: The research will offer insights to policymakers regarding the potential of these strategies for mitigating UHIs, contributing to urban sustainability goals.

4. Awareness and Acceptance: The study may contribute to raising awareness among urban residents about the benefits of these strategies and promoting acceptance of green and biophilic features in the built environment.

The proposed extent of the thesis

60 pages

Keywords

Urban heat island, green roofs, biophilic architecture

Recommended information sources

Chen X, Huang P, Zhou Z and Gao C 2015 A review of green roof performance towards management of roof runoff J. Appl. Ecol.26(8) 2581–90

Liu C, Li Y and Li J 2017 Geographic information system-based assessment of mitigating flash-flood disaster from green roof systems Comput. Environ. Urban Syst 64 321–331

Susca T, Gaffin S R and Dell'Osso G R 2011 Positive effects of vegetation: Urban heat island and green roofs Environ. Pollut. 159(8–9) 2119–2126

Teemusk A, Mander Ü. Greenroof potential to reduce temperature fluctuations of a roof membrane: a case study from Estonia. Build Environ 2009;44:643–50

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Prague on 19. 03. 2024

Declaration

I declare that I have worked on my master's thesis titled " Mitigating Urban Heat Islands through Green Roofs in High-Density Cities (case study: Cairo as an example) " by myself and I have used only the sources mentioned at the end of the thesis. As the author of the master's thesis, I declare that the thesis does not break any copyrights.

In Prague on /03/2024 ___________________________

Acknowledgement

I would like to extend my sincere gratitude to my supervisor, Dr. Peter Kumble, Ph.D., for his unwavering support and guidance throughout my years of study and during the completion of this thesis.

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Mitigating Urban Heat Islands through Green Roofs in High-Density Cities (case study: Cairo as an example)

Abstract

The following research is focused on the causes of Urban heat islands (UHI) and the effects of it on the air temperature and physiological equivalent temperature (PET) and the mitigation measures like green infrastructure, green roofs and living walls while exploring the definition of the green roofs and its history and the situation of the UHIs in Cairo. And this study also evaluates the effects of green roofs on reducing outdoor air temperatures in different urban densities ,with 3 chosen locations in Cairo with the same building height but with different aspect rations between buildings height and width of the street canyons H/W=1,2 and 3 through using an environmental simulation tool called ENVI-met to study each area by simulating reference cases and two scenarios: extensive and intensive green roofs.

Keywords: UHI; Green roofs; Living walls; PET; Cairo; Green infrastructure

Zmírnění městských tepelných ostrovů pomocí zelených střech ve městech s vysokou hustotou (případová studie: Káhira jako příklad)

Abstrakt

Následující výzkum je zaměřen na příčiny městských tepelných ostrovů (UHI) a jejich účinky na teplotu vzduchu a fyziologickou ekvivalentní teplotu (PET) a zmírňující opatření, jako je zelená infrastruktura, zelené střechy a obytné stěny, přičemž zkoumá definici zelené střechy a jejich historie a situace UHI v Káhiře. A tato studie také hodnotí účinky zelených střech na snížení venkovní teploty vzduchu v různých městských hustotách, se 3 vybranými lokalitami v Káhiře se stejnou výškou budovy, ale s různými poměry stran mezi výškou budov a šířkou uličních kaňonů H/W=1 ,2 a 3 pomocí nástroje pro simulaci prostředí nazvaného ENVI-met ke studiu každé oblasti simulací referenčních případů a dvou scénářů: extenzivní a intenzivní zelené střechy.

Klíčová slova: UHI; Zelené střechy; Obývací stěny; PET; Káhira; Zelená infrastruktura

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1.Introduction:

Urbanization has led to the rapid expansion of high-density cities, resulting in various environmental challenges, with urban heat islands (UHIs) being one of the most concerning issues. UHIs are characterized by higher temperatures in urban areas compared to their surrounding rural regions, primarily caused by the replacement of natural surfaces with impervious materials, reduced vegetation, and increased heat-generating activities. Mitigating UHIs is crucial for enhancing urban livability, reducing energy consumption, and promoting overall environmental sustainability. This thesis aims to explore the potential of green roofs, living walls, and biophilic architecture as strategies to mitigate UHIs in high-density cities such as Cairo nowadays after the deforestation that is currently happening due to construction and expanding the roads network.

1.1 The effects do urban heat islands have on measurements of climate change

Although most of the long temperature records available to meteorologists come from in or near urban areas, the weather stations tend to be found in parks and open spaces which are less affected by changes in urbanization. One study has attempted to see how much the urban heat island effect has affected long temperature records, by comparing the temperatures recorded on calm nights (big urban heat island effect) with those recorded on windy nights (less urban heat island effect) – this suggested that the long temperature records were not affected by the urban heat island effect. In other words, any long-term trends in temperature seen in the records were probably the same as if they had been recorded in a rural area. In the last few decades, data from satellites has been added to the records available to meteorologists. The IPCC concluded in their 2007 climate change report:

“Recent studies confirm that effects of urbanization and land use change on the global temperature record are negligible (less than 0.006°C per decade over land and zero over the ocean) as far as hemispheric and continental-scale averages are concerned. All observations are subject to data quality and consistency checks to correct for potential biases. The real but local effects of urban areas are accounted for in the land temperature data sets used [both by excluding as many of the affected sites as possible from the global temperature data and by increasing the error range]. Urbanization and land use effects are not relevant to the widespread oceanic warming that has been observed. Increasing evidence suggests that urban heat island effects also affect precipitation, cloud, and diurnal temperature range.”

2.Aims of the Thesis

The objective of this study is to examine the potential of green roofs as a strategy to mitigate the urban heat island effect (UHI) in densely populated cities like Cairo, where green spaces are scarce, and urbanization takes precedence over greening initiatives. Despite the neglect of building rooftops in Cairo, they represent an underutilized space that could be leveraged for environmental benefits.

Implementing green roofs as a form of urban greening could address this deficiency and have a positive impact on the environment. By introducing green roofs, it is possible to reduce air temperatures within the city and potentially alter the microclimate of urban areas.

Throughout this research, I delve into the concept of green infrastructure and specifically focus on green roofs and living walls considering their historical significance and contemporary relevance, along with exploring the different types of green roofs.

To analyze the effectiveness of green roofs, I utilize the urban simulation software ENVI-met. This software enables the measurement and evaluation of the impact and effectiveness of both intensive and extensive green roofs on air temperature and physiological equivalent temperature (PET).

3. Literature Review.

3.1 Urban Heat Island Phenomenon

The Urban Heat Island (UHI) phenomenon is characterized by higher temperatures in urban areas compared to the surrounding rural areas (Oke, 1982; Voogt and Oke, 2003). The main cause of UHI is urbanization, where natural land cover is replaced by artificial surfaces, resulting in an increase in anthropogenic heat (from impervious paved surfaces, vehicle emissions, exhaust from heating systems, and cooling energy) (Streutker 2003). This transformation of natural surfaces disrupts ecological cycles in the city, reducing evaporation, increasing absorption of shortwave and longwave radiation, blocking wind due to the built-up area, and raising overall temperatures in the city (Senanayake, I., et al., 2010; Mirzaei et al., 2010). Cities that are haphazardly planned and poorly managed are particularly susceptible to UHI due to environmental degradation (Kikon et al., 2016).

While the UHI effect is present year-round, its impact is especially pronounced during summer in warm-climate cities. This heightened concern is attributed to increased exposure to high summer temperatures, leading to a surge in air conditioning demand, elevated air pollution, and a rise in heat-stress-related mortality and illnesses (Rosenfeld et al., 1995).

3.1.2 Causes of Urban Heat Island

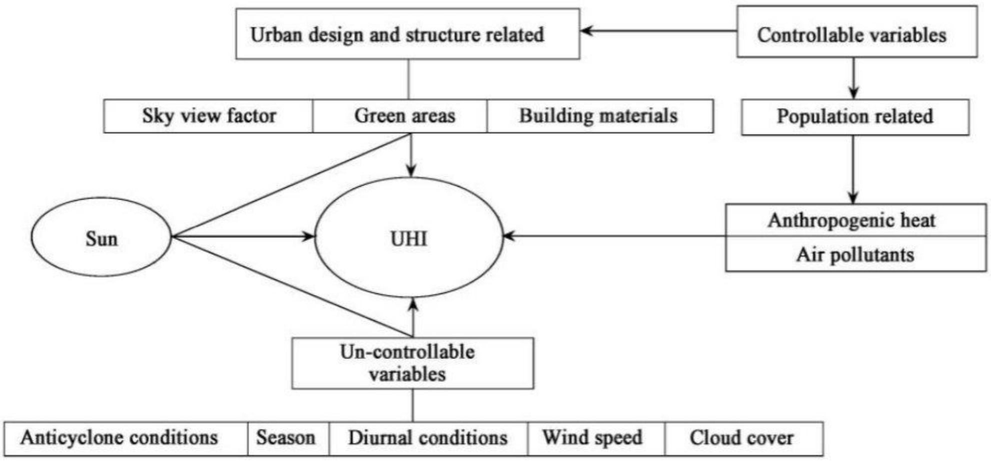


Fig.1 illustrates the creation of the Urban Heat Island (UHI) phenomenon (Rızwan et al., 2017).

Rızwan A. (2017) has classified the factors contributing to UHI generation into controllable and uncontrollable categories. Controllable factors are primarily associated with design and planning matters, allowing for direct influence and control to some extent. In contrast, uncontrollable factors are related to the environment and nature, surpassing humanity's capacity for control.

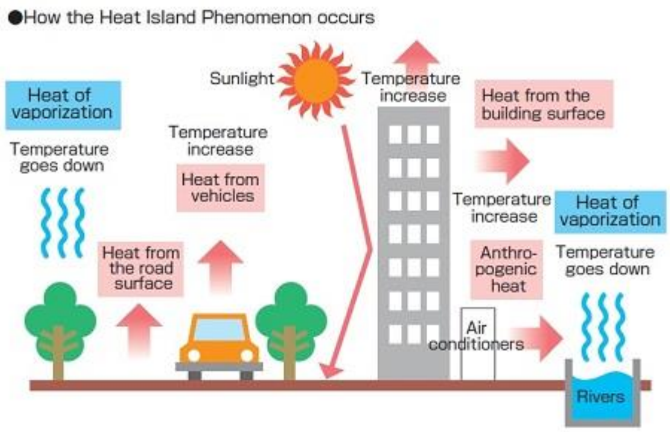


Fig. 2. Factors that contribute to UHI, Source: http://www.gardinergreenribbon.com/heat-island-effect/

3.1.3 Uncontrollable Variables

3.1.3.1 Natural Factors

Geographical variables such as latitude, climate, geographic location (on a mountain or in a valley), topography (including elevation and landforms), and meteorological conditions (including wind, cloud cover, humidity, sunlight, precipitation, etc.) all play crucial roles in the UHI phenomenon and give rise to particular characteristics in each city. Wienert's (2001) study on UHI in 150 cities demonstrated a direct correlation between UHI, geographic latitude, anthropogenic heat generation, radiation equilibrium, and annual variability. Higher latitudes were where the largest variations were observed. This is in line with earlier findings by Oke (1973) that indicated it was important to select areas with approximately equal geographic latitude (Koppe et al., 2004).

(Gedzelman et al., 2003) observed in their New York study that wind speed, direction, and cloud cover all had an impact on UHI. According to Voogt and Oke's 2003 research, increased cloud cover reduces both the UHI impact and radiative cooling at night. UHI may deteriorate in a metropolis during periods of calm winds and clear sky, whereas the opposite occurs during periods of high winds and increased cloud cover (Cheni et al., 2009). According to (Alonso et al., 2003), UHI impacts are more noticeable when atmospheric balance is present, rather than when imbalance is present.

It has been shown that large bodies of water influence local weather patterns (Kusak et al., 2000). Significant water bodies present in urban areas have been associated to a decrease in UHI intensity due to evaporation. The winds blowing from the lake to the coast provide the "LAKE Breeze" effect, which reduces hot summer temperatures around Lake Ontario (Scott and Huff, 1996).

3.1.3.2 Albedo and urban surface materials

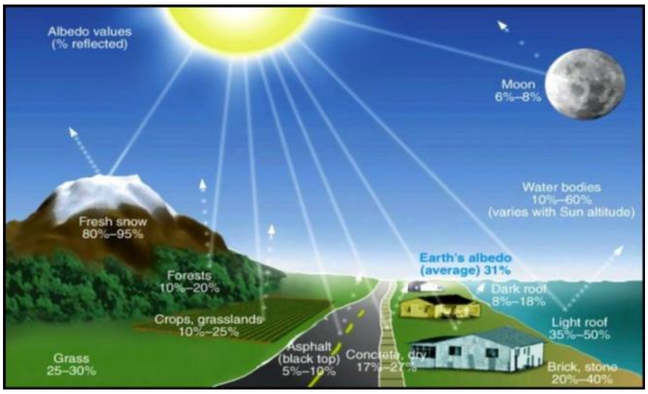


Fig. 3. Albedo rates of objects (Regentsearth, 2017)

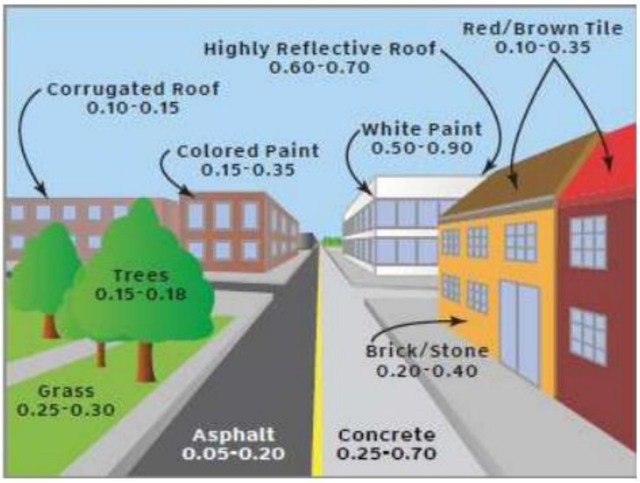
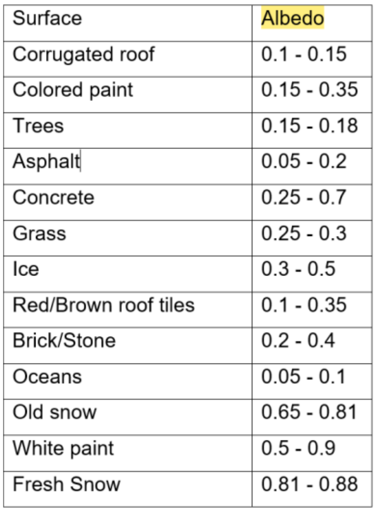


Fig. 4: Albedo ranges of various surfaces typical to urban areas (Source: NASA, Akbari and Thayer, 2007)

When compared to rural areas, the transformation of land cover from vegetation to impermeable surfaces and the use of building materials with varying thermal and radioactive properties (reflectivity and emissivity) lead to changes in the thermal, radioactive, moisture, and aerodynamic characteristics of the surface and the atmosphere (The Green City, 2017).

Albedo, or the ability to reflect sunlight, is described as lighter-colored objects reflecting light more efficiently in the visible spectrum. Albedo, which represents the amount of reflected light, is measured on a scale of 0 to 1. With a mean albedo of 0.31, earth reflects around one-third of radiation back into space.

The albedo values of various surfaces, including cities, deserts, woods, and oceans, vary. According to Esseacourses (2017), woodlands typically range from 0.08 to 0.15 in albedo, whereas deserts typically have an albedo of 0.30. Surfaces with low albedo values, such as rooftops, the walls of high-rise buildings with sharper edges, parking lots, roads, and asphalt and concrete pavements, absorb more solar radiation and transform it into thermal energy (Senayake, et al., 2013).



Surface	Albedo
Corrugated roof	0.1 - 0.15
Colored paint	0.15 - 0.35
Trees	0.15 - 0.18
Asphalt	0.05 - 0.2
Concrete	0.25 - 0.7
Grass	0.25 - 0.3
Ice	0.3 - 0.5
Red/Brown roof tiles	0.1 - 0.35
Brick/Stone	0.2 - 0.4
Oceans	0.05 - 0.1
Old snow	0.65 - 0.81
White paint	0.5 - 0.9
Fresh Snow	0.81 - 0.88

Fig. 5: albedo values of a different kind of surfaces (Kotak et al. 2015).

Heat Islands are created when a city's area of impermeable surfaces surpasses 35 percent; around 72 percent of New York City's surface is impermeable. When impermeable surfaces are replaced with forested areas in sprawling cities, the rate of heat increase in the former doubles when compared to comparable metropolitan areas, resulting in more frequent extreme heat events (Byles, 2017).

3.1.3.3 Factors That Lead to the Formation of and/or influence the Magnitude of UHIs

Table 1. Factors That Lead to the Formation of and/or influence the Magnitude of UHIs

Heat Island Influence	Effect on UHI Magnitude
Surface geometry	UHI magnitude increases as the ratio of building height to street width increases and view of the nighttime sky is obstructed.
Surface thermal properties	UHI magnitude increases with materials that make the city a better storer of heat; those with higher heat capacity and/or thermal

	conductivity relative to rural materials. Variations in rural moisture can influence UHI magnitude.
Anthropogenic heat input	UHI magnitude increases as anthropogenic heat increases. This input can have large seasonal variations in some climates as well as intraurban spatial variability related to the density of development and magnitude of energy use.
City size	UHI magnitude tends to increase with city size up to a limiting amount.
Wind speed	UHI magnitude decreases rapidly as wind speed increases.
Cloud cover	UHI magnitude decreases as cloud cover increases.
Season	UHI magnitude is typically the largest in the warm season in mid-latitudes. In high latitudes, the UHI is the largest in the winter due to anthropogenic heat input. In tropical cities with distinct wet and dry seasons, the UHI is typically largest in the dry season.
Time of day	The canopy-layer UHI is the largest at night (air temperatures). The surface UHI magnitude is larger during the day (clear, sunny conditions).

Source: Adapted from Arnfield.

These factors are most directly related to the canopy-layer UHI but also affect other UHI types.

3.1.4 Controllable Variables

3.1.4.1 Urbanization and Anthropogenic Heat

Urbanization is known to have a significant impact on regional weather and climate, as evidenced by numerous studies (Landsberg 1981). Urban population density is predicted to increase further, with the majority of people living in urban areas in Egypt by 2050, for example (WHO, 2018). The pollution load in urban areas is higher than in adjacent rural areas. Pollution—especially aerosols—can create a deceptive greenhouse effect by reflecting and absorbing long-wave radiation, which prevents surfaces from cooling through radiation (Streutker 2003).

The use of fossil fuels for transportation and the heating and cooling of built infrastructure are two important anthropogenic heat sources that contribute to the Urban Heat Island (UHI) effect (Sailor & Lu, 2004). Moreover, the function of structural insulation is connected to the rise in temperature caused by anthropogenic factors (Arnfield, 2003). The impact of anthropogenic factors on urban heat island (UHI) is also dependent on the area's size, population density, and climate, which makes it less noticeable in small towns than in large cities (Oke, 1982).

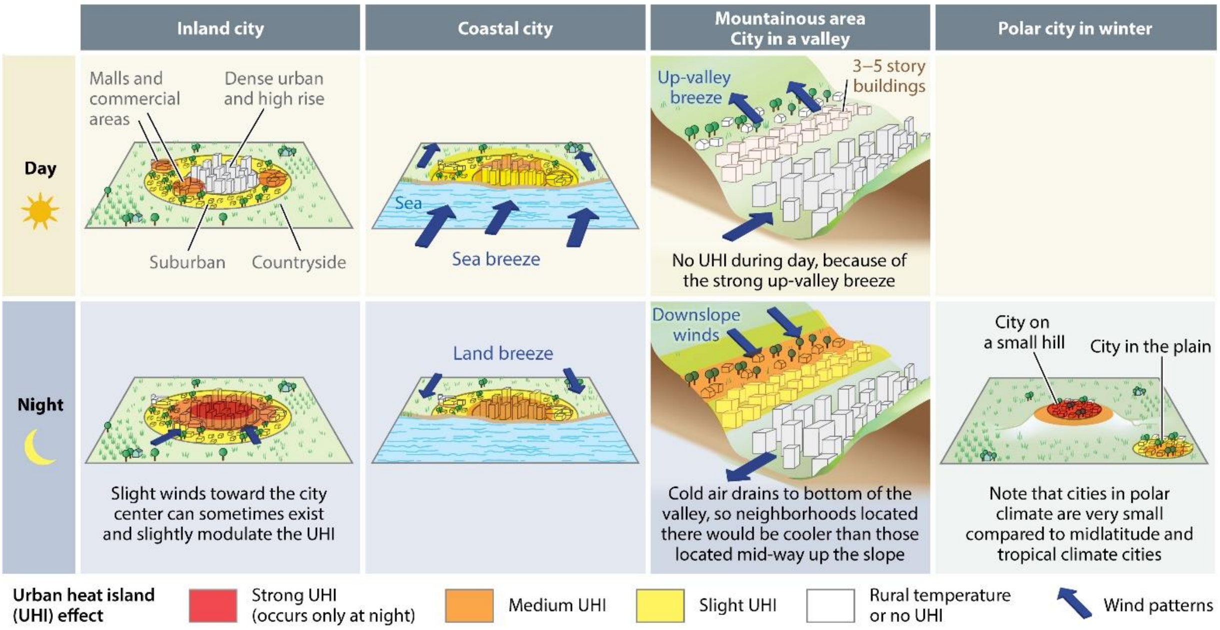
3.1.4.2 Urban geometry

Size, shape, composition, and neighborhood planning affect the level of UHI (Chen et al., 2006). The reduction in air circulation and the overall decrease in the temperature within cities are mainly caused by skyscrapers and cramped streets, which trap heat accumulated throughout the day (Bokaie et al., 2016).

Assembled thickness and manufactured shape are composite factors consolidating parameters, for example: areas of uncovered outer surfaces, the thermal capacity and surface reflectance of fabricated components, and the perspective of sun and sky by surfaces (Koppe et al., 2004).

Undeveloped ground receives three times less annual radiation than a cubical structure does. Rural areas usually have higher wind velocities than that of cities. Due to this, convective cooling is less effective thus lowering the rate of heat dissipation. Convoluted airflow patterns and turbulence are a result of the channeling effect of urban canyons, which are formed by tall buildings (Koppe et al., 2004).

Sky View Factor (SVF), the proportion of the sky “viewed” from a fixed spot, is a frequently studied part of urban geometry. An open space parking lot with small amounts of stuff blocking the view would have a high SVF, but an urban canyon would have a low SVF, due to the tall buildings. This SVF is a reason for increased urban heat islands in cities because radiation accumulated daily cannot escape to the open sky because of tall buildings that trap the radiation. In the two urban centers of Japan, Fuchu and Higashimurayama, there is a correlation amidst air temperature and SVF (Yamashita et al., 1986).



Masson V, et al. 2020.
Annu. Rev. Environ. Resour. 45:411–44

Fig. 6: Topography and its effect on UHI.

source: https://www.annualreviews.org/doi/full/10.1146/annurev-environ-012320-083623

- Topography: Urban areas are often located in valleys or basins, which can trap heat and prevent it from escaping. This is because warm air rises, and when it reaches the top of the valley or basin, it has nowhere to go (figure 6). This can create a "heat dome" effect, where the temperature in the urban area is significantly higher than the temperature in the surrounding rural areas.
- Atmospheric conditions: Calm winds and clear skies can allow heat to build up in urban areas. This is because winds can help disperse heat, and clouds can reflect sunlight back into space. When there is no wind and no cloud cover, heat can build up in urban areas and contribute to the UHI effect (Oke, 2008).

3.1.4.3 Lack of vegetation

The ecological benefits provided by vegetation, such as evapotranspiration, humidification, shade, and stormwater management, have a significant impact on reducing temperatures in each region. However, when these ecological services and natural cycles are disrupted, it can lead to higher temperatures in urban areas compared to rural areas. (EPA, 2008).

3.1.5 Urban Heat Island Types

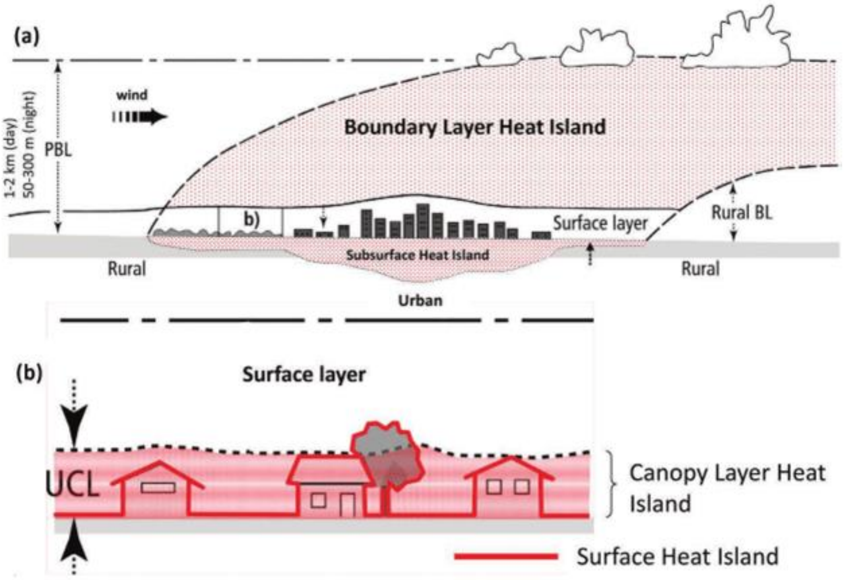


Fig. 7 Schematic diagram showing the different heat island types and their locations within an urban area. Shading represents the affected volume, but it does not show the expected spatial variations, (a) Under fair weather conditions, within the first l-2km of the atmosphere, known as the planetary boundary layer (PBL), a boundary-layer heat island exists with a characteristic plume shape extending in the downwind direction, (b) Within the UCL air volume, a canopy-layer heat island exists (warmer air temperatures). The surface heat island consists of all surfaces, but usually only a subset of these surfaces can be seen from any one observation point. Below the surface, a subsurface heat island exists. (Adapted from Oke,1997.)

Heat Island Type	**Variable Affected**	**How Measured**	**Spatial Characteristics**	**Temporal Characteristics**
Canopy layer heat island	Air temperature	Fixed or mobile (vehicle-based) measurements using thermometers.	Shows significant spatial variability associated with important elements of surface structure: building height-to- width ratio, amount of vegetation, topographic features.	Largest at night. Magnitude grows rapidly in the late afternoon and early evening. May be negative (a cool island) during the daytime. Highly sensitive to wind and cloud.
Boundary -layer heat island	Air temperature	Thermometers mounted on very tall towers, balloons, kites, or aircraft. Remote-sensing from ground-based instruments.	Exhibits a “domed" structure in near-calm conditions and a distinct downwind “plume” as winds increase. Boundary-layer depth is 1-1.5 km by day, but only 50-300 m at night. Heat island magnitude decreases with height in the boundary layer by night and is approximately constant by day.	Shows relatively small diurnal variation. Sensitive to wind and cloud.
Surface heat island	Surface temperature	Remote sensing from towers, aircraft, or satellites.	Significant spatial variability associated with variations in surface characteristics, including shading, surface orientation, moisture status, thermal properties, surface reflectivity, and vegetation coverage. Variability of rural surface temperature is also large and affects heat island magnitude.	Largest during daytime in the summer season. Nighttime value is also positive and largest in summer. Highly sensitive to weather conditions. Varies with season especially if there are significant changes to moisture or vegetation characteristics or where substantial winter heating is used.
Subsurface heat island	Ground temperature	Ground or borehole temperature measurements.	Spatial variability occurs due to variations in surface characteristics and subsurface heat sources from urban infrastructure. Urban areas show a greater depth of temperature decrease from the surface before temperatures reverse to show the geothermal gradient.	Temporal response is increasingly lagged with depth so that subsurface patterns reflect past conditions at the surface. Temporal influences below the first meter are typically only seasonal or longer.

Table 2: Heat Island Types and Their Spatial and Temporal Characteristics

3.1.5.1 Atmospheric Urban Heat Islands

According to Oke and Voogt (2003), the Urban Canopy Layer (UCL) is a layer of urban atmosphere that extends from the surfaces of buildings where people live to the rooftops of trees and buildings. UCL is influenced by the surrounding urban space and is considered to be unaffected by sensors at classical meteorological elevations or by passing transit-attached sensors. Above the UCL is the urban boundary layer (UBL), which extends no farther than 1.5 km from the ground. The UBL spans from the peak of average building elevation to urban landscapes and is influenced by the surrounding atmosphere.

To measure UBL heat island, customized sensor platforms such as high towers or airplane-attached equipment, as well as radiosonde or tethered balloon flights, are used (Voogt and Oke, 2003).

3.1.5.2 Surface Urban Heat Islands

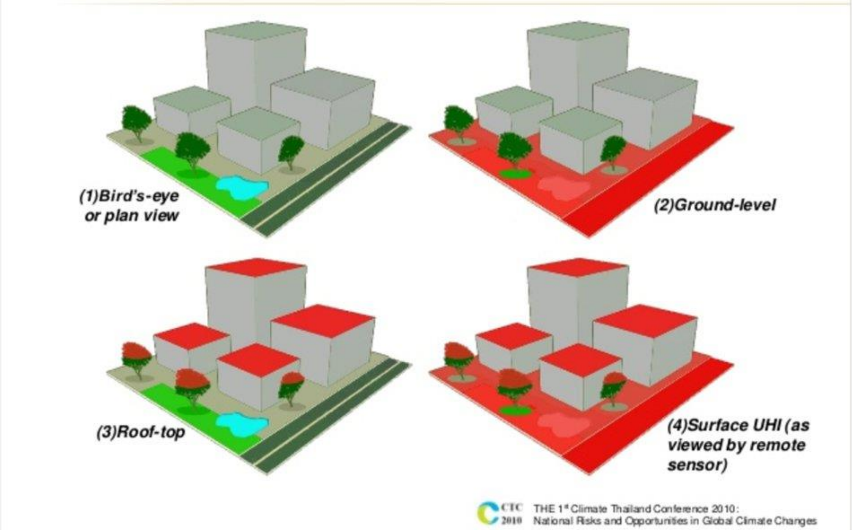


Fig. 8. Surface Urban Heat Island (The 1st Climate Thailand Conference 2010: National Risks and Opportunities in Global Climate Changes /Chiang Mai 2010)

The Surface Urban Heat Island (SUHI) phenomenon refers to the difference in temperature between urban areas and their surrounding regions, which can be measured indirectly through thermal remote sensors on airplanes or satellites. This method is also known as remotely sensed UHI and provides an alternative to direct measurement options such as meteorological stations. (Cochran, 2014).

3.1.6 Impacts of UHI

According to Voogt (2002) and E.A (2017), the Urban Heat Island (UHI) phenomenon has various negative effects on urban living and the ecological environment. These effects include a decline in air and water quality, an increase in greenhouse gas emissions and air pollutants, higher energy expenses, and disruptions to overall livelihoods and physical well-being, among others. The phenomenon also presents health risks to vulnerable populations such as the elderly and young, who are affected by temperature fluctuations. Studies from different domains have examined UHI's effects on urban living, including urban ecology, urban planning, urban climatology, and urban geomorphology (Estoque et al., 2017).

The rise in temperatures during heat waves can result in severe health problems such as heatstroke, heat cramps, dehydration, and heat-related fatalities, as Fouillet et al. (2006) and Whitman et al. (1997) have shown. The problem is exacerbated by photochemical smog, which is brought on by urban pollution and the combination of contaminants from urban surfaces. UHI exacerbates the severe contamination of drinking water, contributing to river pollution by gathering dirt, heat, and hazardous materials from impermeable surfaces (Kraus et al., 2004; Finkenbine et al., 2000).

Moreover, UHI has impacts on local climates, including variations in precipitation, clouds, and daily temperatures, as reported by the Intergovernmental Panel on Climate Change (EPA.gov, 2017).

3.2 Green infrastructure.

3.2.1 Definition of Green Infrastructure

There are wide ranges of definitions of GI in the present literature of researchers and organizations.

Reference	**Explanation**	**Scale of application**
Benedict and McMahon (2006)	Green infrastructure is an interconnected network of natural areas and other open spaces that conserves natural ecosystem values and functions, sustains clean air and water, and provides a wide array of benefits to people and wildlife	Landscape
European Environment Agency (2011)	Green infrastructure is a concept addressing the connectivity of ecosystems, their protection and the provision of ecosystem services, while also addressing mitigation and adaptation to climate change. Green infrastructure helps ensure the sustainable provision of ecosystem goods and services while increasing the resilience of ecosystems.	Landscape

Landscape Institute (2009)	Green infrastructure is an approach to land use, underpinned by the concept of ecosystem services. Green assets such as parks, coastlines or embankments have generally been thought of in terms of their single functions — the approach that recognizes their vast range of functions and their interconnectivity is called green infrastructure.	Landscape / Multi-scale
Tzoulas et al. (2007)	The concept of Green Infrastructure can be considered to comprise all natural, semi-natural and artificial networks of multifunctional ecological systems within, around and between urban areas, at all spatial scales.	Multi-scale
European Commission (2013)	Green Infrastructure can be broadly defined as a strategically planned network of high quality natural and semi-natural areas with other environmental features, which is designed and managed to deliver a wide range of ecosystem services and protect biodiversity in both rural and urban settings.	Multi-scale
Forest Research (2010)	Green infrastructure refers to the combined structure, position, connectivity and types of green spaces which together enable delivery of multiple benefits such as goods and services. It is important to consider green infrastructure holistically and at landscape as well as individual site scale.	Multi-scale
Natural England (2010)	Green infrastructure is a strategically planned and delivered network of high-quality green spaces and other environmental features. It should be designed and managed as a multifunctional resource capable of delivering those ecological services and quality of life. benefits required by the communities it serves and needed to underpin sustainability. Green infrastructure includes established green spaces and new sites and should thread through and surround the built environment and connect the urban area to its wider rural hinterland.	Urban
Ahern (2007)	Green infrastructure is a concept that is principally structured by a hybrid hydrological/drainage network, complementing, and linking relict green areas with built infrastructure that provides ecological functions. Green infrastructure plans apply key principles of landscape ecology to urban environments.	Urban
Sandström (2002)	Green infrastructure' concept is introduced to emphasize the multiple purposes of green space (including ground and surface water). In current efforts to achieve sustainable urban development, 'green infrastructure' has the same dignity as 'technological infrastructure' has had in traditional urban planning.	Urban
EEAC (2009)	Green infrastructure is the actions to build connectivity nature protection networks as well as the actions to incorporate multifunctional green spaces in urban environment.	Urban

Table 3, Examples of GBI definitions (Pachapski, 2021, Barikany, 2022)

The concept of green infrastructure, according to the Green Infrastructure Guidance provided by Natural England, primarily pertains to urban areas and emphasizes its role in providing ecosystem services and improving the quality of life through the provision of green spaces within communities (Natural England, 2010). Several studies highlight the importance of assessing green infrastructure across multiple scales, stressing its necessity as a continuous network, whether conceptually or in practical terms, and its impact on social well-being (Tzoulas et al., 2007; Forest Research, 2010; European Commission, 2013). Sandström (2002) and Ahern (2007) provide specific definitions of green infrastructure on an urban scale, considering the correlation of greenery with hydrological elements, particularly drainage systems, ground, and surface water. Sandström (2002) even asserts that green infrastructure holds a status comparable to that of technological infrastructure in urban planning. The American perspective views green infrastructure as a network of hydrological components, often applied to the management of stormwater runoff through natural systems (EEA, 2011). However, certain American institutions, such as the Conservation Fund, utilize the term more broadly, acknowledging the broader benefits of green infrastructure (Benedict & McMahon, 2006).

Ahern (2007) aligns with applying landscape ecology principles to urban green infrastructure, emphasizing the relevance of key ideas from landscape ecology, such as a multi-scale approach and a focus on physical and functional connectivity.

3.2.2 Benefits of Green Infrastructure (GI)

Integrated Green Infrastructure (GI) offers a range of benefits such as improving water quality, reducing hydrological extremes, mitigating the impact of urban heat islands, promoting energy savings, enabling carbon sequestration, and improving the overall ecology of cities.

These advantages are interconnected and have a significant influence on one another. Therefore, it is crucial to conduct comprehensive evaluations of integrated services in GI implementation, taking into account social and physical advancements. Several authors, including (James et al.,2009) and (Wahler et al.,2014) support this viewpoint.

3.2.3 The role of GI against the climate change

In 2014, the Intergovernmental Panel on Climate Change (IPCC) identified global warming and greenhouse gas emissions as the primary causes of the Earth's changing climate. The urban heat island effect, which is exacerbated by these factors, can be mitigated by the implementation of green and blue infrastructure (GI) in urban environments. This infrastructure is crucial in addressing the specific effects of climate change on cities. Urban areas tend to have warmer temperatures and denser surfaces than their peripheries and non-urban areas. This is partly due to the materials in roads, pastures, and buildings, which have the ability to absorb heat. Increasing green cover in urban areas through GI implementation causes incident radiation to be reflected into the atmosphere, creating a cooling effect.

According to various sources, such as (CABE, 2010) and (Schaffler et al., 2013), the implementation of GI in urban areas is seen as a long-term and economical measure to address climate change. Rising sea levels, more intense and frequent storms, and extreme temperature and precipitation events are some of the anticipated effects of climate change (Malik et al., 2018; Milly, 2012).

Given that average annual summer and winter temperatures are predicted to rise in metropolitan areas due to climate change, the use of GI presents a potential way to lessen the impact, particularly on summer temperatures (SURF, 2011). The implementation of GI not only improves the environmental performance of cities but also increases their livability, providing a step in the right direction towards addressing climate change challenges (Din Dar et al., 2021).

3.2.3.1 Temperature mitigation

According to some authors, urban microclimates have significantly higher wind speeds, higher temperatures, and less rainfall than natural or rural areas (Santamouris, 2013). Thus, improving urban areas' microclimate especially by incorporating elements like urban forests and trees stands out as a notable environmental advantage of green infrastructure (GI) (AILA, 2012). Higher temperatures linked to urban heat islands exacerbate precipitation events in these areas by promoting climate variability in urban microclimates (Liu and Niyogi, 2019; Simsek and Odül, 2019).

Via two primary natural processes, plants and trees play a crucial role in influencing the urban microclimate and reducing the impact of the Urban Heat Island effect. Firstly, they shade urban areas to provide a cooling effect and improve humidity and transpiration impacts on air conditioning.

Increasing a city's green space can have a major impact on daily temperatures, and studies have examined the potential cooling effect in a variety of climate scenarios. As an example, Gill et al. (2007) modeled the green cover in Manchester, UK, and their findings indicated that it could be possible to keep maximum surface temperatures well below those recorded between 1961 and 1990 until 2080, especially in urban centers and high-density residential areas.

Additionally, studies show that a 10% decrease in greenery, replaced by concrete and impermeable surfaces, may lessen the cooling effect and increase the maximum temperature to about 35 °C. On the other hand, a 10% increase in green cover achieved by planting tree canopies beside roads may limit summer temperatures to a maximum of 29 °C (Gill et al., 2007). Although these evaluations were carried out for Manchester City, they may have implications for other urban areas and cities.

Similarly, it has been discovered that building green walls and facades in worm habitats lowers surface temperatures by 1 to 15 °C (P'erez et al., 2014).

3.2.3.2 Energy savings

Energy availability and consumption are closely linked to a country's economic prosperity, which forces nations all over the world to look for ways to reduce their energy consumption and demand (Banking on Green, 2012). A more sustainable and practical approach to lowering energy costs for cooling buildings in cities with a warm climate is the adoption of green roofs (Bayram and Ercan, 2012).

By reducing surface and air temperature, urban green infrastructure (GI) plays a crucial role in climate change adaptation, directly leading to increased thermal comfort and decreased energy use. Hygienic indicators like room temperature, energy savings, and turbulent flows confirm the reduction in energy consumption and improvement in thermal comfort associated with GI selection.

Extended urban green spaces, green roofs, and roadside trees significantly reduce the cooling and heating demands of individual buildings, improving energy efficiency, according to research (Banking on Green, 2012). According to Heisler (1986), GI can lower cooling expenses by 20–50% and heating costs by 10-15% in residential areas that have trees. Increasing the amount of green cover can further reduce the total energy used for heating and cooling by 10% and 5%, respectively, according to a study done in Chicago, US—a city leading the way in the installation of green roofs. Approximately 50% of Chicago's buildings have green roofs installed, saving $3600 year on energy costs per structure (Banking on Green, 2012).

Due to variations in estimating the various advantages and energy costs associated with GI installations at different scales, quantifying the overall benefits of GIs poses challenges. However, numerous studies and examples point to significant energy and environmental savings and advantages from GI development (Banking on Green, 2012). Because they naturally lower the optimal temperature in urban areas, GIs are anticipated to reduce energy requirements and related health risks. To summarize the previous discussion and make reference to Table 4, the results of green infrastructure development, including green roofs (Table 4), show a significant decrease in heat input and surface temperature when compared to conventional roofs without vegetation cover (Barikany 2022).

Location	Thermal Reduction	Study
Reunion Island, Indian ocean	6.7 °c (Roof surface)	Moray et al., (2012)
Tamuna Nagar, India	5.1 °c (Indoor air)	Kumar and Kaushik, (2005)
New York city, USA	2 °c (Indoor air)	Susca et al., (2006)
Singapore	7.3 °c (Roof surface)	Qin et al., (2013)
Kuala Lumpur, Malaysia	1.5 °c (Indoor air)	Kok et al., (2013)
Cascavel, Brazil	4.96 °c (Indoor air)	Cassia et al., (2018)

Table 4. the reduction of temperature due to green roofs

3.3 Green Roofs

3.3.1 Definition of green roofs

Construction activity consistently aligns with economic development, and projections indicate that by 2030, there will be an estimated 43 megacities (United Nations. Department Of Economic and Social Affairs. Population Division, 2019), each with a population exceeding 10 million. The expansion of the building sector is directly linked to a 3% increase in greenhouse gas emissions from 2000 to 2010, coupled with heightened energy consumption resulting from human activities. Notably, almost 40% of the world's total energy consumption is attributed to the building sector (World Energy council 2013). Given the susceptibility of residential areas, it becomes imperative to implement mitigation strategies across private and governmental sectors and countries, especially in domains significantly reliant on fossil fuels.

As building roof surfaces cover 20–25% of urban areas, they present a viable opportunity to reduce both surface and air temperatures in urban settings. Green roofs, categorized as either extensive or intensive with naturalistic or self-established vegetation, are horizontal living systems that effectively address various environmental issues. Terms like "green roof," "living roof," "eco-roof," "vegetated roof," and "rooftop garden" describe these structures. A green roof is defined as a human-made installation on a building's roof, involving the construction of a structurally robust framework. Another definition, proposed by Yu et al., refers to a building roof that is either wholly or partially covered with vegetation and a growth medium, whether flat or sloped, designed to support vegetation while serving as a fully functional roof.

The components of a green roof encompass plants, a substrate for nutrient provision, a water system for root growth support, and a drainage layer to eliminate excess water. In essence, a green roof creates an environment conducive to sustaining plant growth. Figure 8 classifies and compares three types of green roofs based on their functions and costs, considering factors such as structural systems, plant types, prevalence, and installation costs. It's essential to note that the final cost may vary across countries and among different green roof installers for these roof types (Abass et al., 2020).

3.3.2 History of Green Roofs

Green roofs in the 20th century, in the early modern era, different continents kept the idea of the green roof alive; this concept was broadly adopted in various regions and cultures. In the mid-1880s, the new technology brought the idea of a living roof on the top of the concrete roof, the first model of this roof appeared in the World Expo in Paris in 1867. The model illustrates a green roof with waterproofing and drainage system, which considers the first design of an extensive green roof (Dunnett N and Kingsbury, 2008). During the 20th century, the originators of modern architecture (Le Corbusier, Alvar Aalto, and Frank Lloyd Wright), start to implement the green roof and walls in their design to merge the natural with construction. Their famous designs are a clear sign of this concept (Villa Shodhan, Villa Mairea, and Millard House).

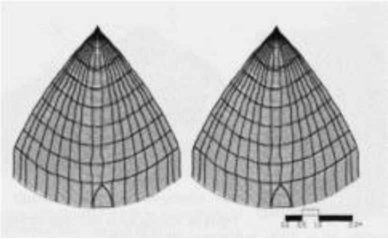
In the late of 20th century, the appearance of the industrial era can be traced back the concept of green roof in Germany, after the innovation of mixed gravel and sand with tar to produced non- inflammable waterproof by a roofer named H. Koch. With the help of nature, the new materials became the base system to herbaceous plants that grow on building’s roof, later in the 1960s, both sand and gravel layers were replaced with simple drainage system and new design of lightweight green roof (Jim, 2017). The innovation and development of roof technology made German the first country in the world adopted the principle of green roof in the building followed by North Europe and North American and Finally a few countries in Asia.

3.3.3 Green roofs in a hot climate.

The definition of a hot climate in this section refers to the Mediterranean, tropical, steppe, and hot climate. These climates adopted green roofs as construction elements or upper ground garden in both vernacular and monumental architecture in Asia, Africa, Eurasia, America, and Australia. The first appearance of the green roof was in Ziggurat of Ancient

Mesopotamia (Osmundson T,1999), from the fourth millennium until 600 BC. The green roof located in the courtyard temples, shrubs and trees were planted at terraces formed by a gran-stepped pyramid. Whereas the most famous type of green roof which was constructed at about 500 B.C. is “The Hanging Garden of Babylon” that known as the first botanic garden in the world, whereas various types of plants that do not exist in the community were cultivated. In the Mediterranean era, the existence of the green roof was found in Pompeian buildings were the patch of green in the heart of the city.

The appearance of the green garden in the shape of an Atrium is not only found in public spaces and but on the roof of dwellings building. Villa of the Mysteries (Villa Dei Misteri) is evidence of intensive roof garden in Pompeii, according to Osmundson (Osmundson et al.1999), the entrance of the house is clear evidence of the roof garden, while the façade is a kind of hanging garden. The previous paragraphs presented a brief of some examples of green roof that existence in monumental architecture, whereas used to mitigate the hot climatic condition, as a recreational area, or to express the social status of the owner. Not far away from the concept of green roof of monumental architecture, the appearance of a dry roof in vernacular architecture due to the lack of water in some areas, the use of bamboo, grass, leaves, and reeds as construction element were found in different regions, times, and civilization (Alexandri 2005). In table 5, a comparison of different types of green roof that exist in vernacular architecture in other regions and civilizations with hot climate is highlighted.

Figure	Description
	Dome-shaped dwelling made from dry reeds and covered by dry grass in Zulu Land (Oliver P1997). Dwellings designed with round or geometrical shapes were covered with dry grass on the top of clay, stone houses or grass houses. The thatched roofs used since ancientness time until now, to cope with the hot climatic condition.
	In some Europe countries, the thatched roof used commonly to keep out the heat far away from the indoor. The designs of the house are different from one area to another. As showing in figure two, grass hunts were used by the farmers in Greece as a temporary shelter and storing area.

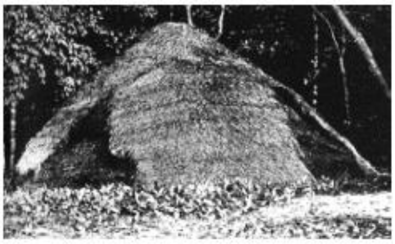
	In Asia, dry plants used as a raw material to construct their settlements in China, India, Japan, and Indonesia. Turf roof used by villagers to cover their straight, curved, or even pyramids roof shape. The figure shows a pyramid shaped thatched hut in Bay. Thatched roof and walls were considered a technique to mitigate the climate condition.

Table 5. Adapted from F Abass et al., 2020 IOP Conf. Ser.: Mater. Sci. Eng. 713 012048

3.3.4 Green roofs in cold climate

In cold environments, green roofs are prevalent, and the scarcity of water is typically not an issue in this climate. Therefore, green roofs serve as a form of insulation material, reducing heat losses from the inside to the outside. The use of dry grass as a thatched roof and in construction materials dates to prehistoric times and has been observed in various regions of Europe, including Germany, Poland, France, some Scandinavian countries, Ireland, and Britain.

The presence of green roofs is also uniquely evident in burial construction, where the burial site, situated under a hill covered with grass and plants, features a pathway to chambers. The layout of burials could be small, large, single, twin, or triple. These straightforward designs allowed prehistoric communities to imprint their presence on the landscape. Man-made burials were also utilized by various ethnic groups, such as Vikings, Celts, Pagan Saxons, and ethnic groups in central Europe.

The time frame for these practices is estimated to be between 1500 to 800 B.C. for Scandinavian groups and 1400 to 1200 B.C. for ethnic groups in the South of France (Donnelly, 1992), continuing into the period of Christianity. As an adaptation to the green roof concept observed in burials since 1500 B.C., the use of reed roofs became prominent in sacred places, such as churches during the period of Christianity and also in mosques found in Africa. English traveler John Barrow recorded in 1796 the application of a thatched roof in Thingvellir church. Additionally, Sifrastadir church (built-in 1842) in Northern Iceland and Vidmyri church were also designed with green living roofs (Alexandri, 2005).

Table 6. Examples of living/ green roof found in vernacular architecture in a cold climate.

Figure	**Description**
	The turf wall and turf pitched roof were essential elements used during the Viking era to protect the building from a low temperature during winter. This technique dated from 800 AD until the late 9th century. The figure presents a living roof in the Mallhaugen Open Air Museum in Lillehammer, Norway.
	The idea of turf roofs and walls was discovered in North America, specifically in L'Epaves Bay, Newfoundland, and L'Anse. According to (Donnelly M C1992), turf roofs covering the ground and the tops of winter houses or oval family settlements were observed among the Yup'ik Eskimo in Alaska. The attached figure illustrates large vertical dwellings covered with turf at Yukon River, Alaska.
	This illustration shows a dwelling in Canada with a living grass roof. In the 19th century, Russian migrants introduced their green roof technique to Canada. Additionally, the figure showcases turf walls and roofs in miners' dwellings at Thompson River Valley in Canada. Dry twigs and turfs were utilized as construction materials to insulate the indoors from the cold climate.

Adapted from: Abass et al., 2020.

3.3.5 Green Roofs Nowadays

Subsequently, the adoption of green roofs expanded across northern Europe, especially in Germany, for rural and agricultural purposes. The 1880s witnessed a surge in urbanization and industrialization in Germany. To mitigate the fire risk posed by roofing low-cost housing with flammable tar, a roofer named H. Koch introduced a sand and gravel base. Over time, unintended seeds naturally germinated in the substrate, giving rise to green meadows across the industrialized skyline (Francis and Lorimer, 2011).

One of the earliest instances of a planted concrete roof in Europe was showcased at the EXPO in Paris 1867, where attendees had the opportunity to explore extensive green roofs and witness a "concrete nature roof" exhibit (Dunnett and Kingsbury, 2008).

Due to the economic situation and the limited availability of labor, roof greening saw a notable decline during the Great Depression and World War II. In the 20th century, there was a resurgence of interest in building green roofs for environmental reasons and bringing nature back into the lives of citizens. This conversation was surrounded by visionaries of contemporary architecture, such as Le Corbusier, Frank Lloyd Wright, and Silvio Alto. In Le Corbusier's "Five Points of a New Architecture," for example, roof gardens had a secondary role. These five points became influential principles that shaped a variety of conventional architectural projects.

Prominent examples of modern green roofs: the Rockefeller Center rooftop green gardens in New York, considered the first modern green roofs in the US (1930) (Figure 9).

Fig. 9: (A) Green gardens at the top of Rockefeller Centre in New York, (B) Roof garden at Villa Mairea designed by Alvar Aalto, (C) Green roofs at Monastery of La Tourette designed by Le Corbusier’s.

Modern green roof technology flourished in the 1960s, with Germany setting the standard for strong technological development that incorporated advanced irrigation and roof incursion prevention. This innovation paved the way for the widespread use of green roof technology. Large-scale research on green roof layers, including root membranes, waterproofing membranes, drainage and filter layers, and growth media, was carried out in the 1970s, particularly in Germany, Switzerland, and the Nordic nations. The German green roof market had notable expansion in the 1980s, with an annual growth rate typically ranging from 15% to 20%. Germany installed one million m2 of green roofs by 1989, and by 1996, that number had increased to ten million m2 (Ermakova and Muiková, 2009).

This growth was facilitated by state legislation, local grants, and policies, setting an example for other European nations. Rooftop and vertical gardening have been incorporated into by-laws and planning regulations in several medium and large-sized European cities, becoming a common element in the urban landscape and construction sector in countries like Germany, France, Austria, Norway, and Switzerland.

Presently, the adoption of green roofs is a global phenomenon, particularly prevalent in developed countries across Europe, North America, and Asia. Initial investigations into green roofs were conducted in European nations like Switzerland and Germany, laying the foundation for acknowledged guidelines and standards such as FLL (FLL, 2008; Dvorak and Volder, 2010).

3.3.6 Types of green roofs

In Figure 10, various green roof types are depicted, yet they share common key components, including weight, biotic elements, substrate, succession, drought tolerance, and the roof's environmental significance in their design (Mentens et al., 2006). A third category, known as semi-intensive, has evolved as a hybrid of the other two (Ampim, 2010).

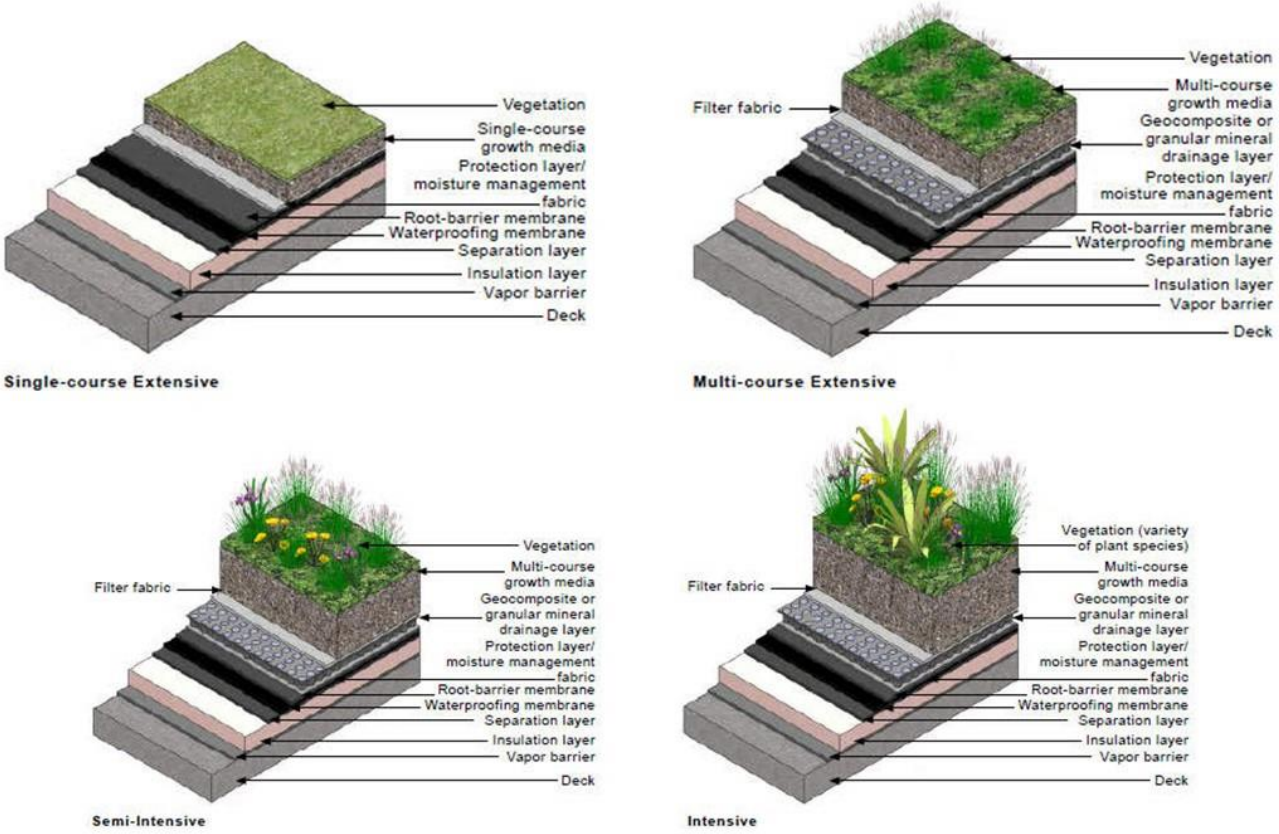


Fig. 10: An illustration of the four green roof types and their components. Semi-intensive roofs were not used in the data collection. Source: (Sustainable Facilities Tool 36)

The distinct purposes and specific characteristics of each type underscore the significant variations among them. Table 7 provides a classification and comparative overview of green roof types.

Table 7. Green roof types

Type	Intensive	Semi-intensive	Extensive
Loadbearing component	Concrete (max. pitch 5%)	Concrete	Concrete, wood
Plant choice	Lawns/perennials, shrubs, trees	Perennials, grass, herbs, small shrubs, lawns	Sedums, herbs, mosses, perennials
Thickness of growing medium	300 and over mm	120-300 mm	40-150 mm
Weight of complete system (kg/m2)	500 to 2000	200 to 500	75 to 180
Irrigation	Yes	Yes	No
Maintenance	Very High	High	Low
Cost	High	Periodic	Low
Accessibility	Yes	Limited	No

Source: adapted from Tailor ,2010

3.3.6.1 Intensive Green Roofs:

As previously highlighted, intensive green roofs, often referred to as "roof gardens," function akin to traditional gardens or recreational spaces and feature a soil layer exceeding 150 mm (refer to Table 7). Characterized by a substantial soil depth, diverse vegetation, and increased weight-bearing and stress loads, intensive green roofs require robust structural support and elevated maintenance efforts. Typically constructed on slopes less than 10 degrees, these roofs support various plant types such as vegetables, grasses, perennial herbs, shrubs, and even trees.

The primary advantage of intensive roofing systems is their capacity to enhance biodiversity and foster a more natural environment. In terms of runoff reduction and water quality alteration, intensive green roofs outperform extensive ones significantly. For instance, they can reduce runoff by 85%, while extensive green roofs achieve a 60% reduction. Moreover, runoff from intensive green roofs shows significantly lower levels of lead, zinc, cadmium, and copper contamination compared to extensive green roofs.

3.3.6.2 Semi-Intensive Green Roofs:

Semi-intensive green roofs, as seen in Table 7, represent a hybrid between extensive and intensive types. Requiring periodic irrigation and modest upkeep, these roofs can support a diverse ecology and handle more runoff than extensive green roofs. With a growth medium layer less dense than intensive green roofs, semi-intensive roofs offer the potential for amenity use. Planting options include ground coverings, grasses, small herbaceous plants, and compact shrubs.

3.3.6.3 Extensive Green Roofs:

Extensive green roofs, characterized by thin soil depth and fewer layers (F.L.L., 2008), boast easier maintenance and greater accessibility. The major advantage lies in their cost-effectiveness, with the main specifications detailed in Table 7. The substrate layer in extensive green roofs does not exceed 150 mm, making them suitable for installation on sloped roofs, sometimes up to 45 degrees. Dominated by tough sedum species, these roofs are low-growing, drought-tolerant, require minimal nutrients, have low biomass, experience minimal seasonal die-back, and pose little fire hazard. The widespread adoption of extensive green roof technology in the 1980s has contributed significantly to sustainable urban ecology, given their lightweight nature and suitability for various rooftops. This dynamic and customizable technology allows buildings to select the most suitable green roof type, involving a larger population in the practice of sustainable green roof development. (Fig.11)

Fig. 11: Example of extensive green roofs. Source: https://www.vegetalid.com/solutions/green-roofs/what-is-an-extensive-green-roof/concepts.html

3.3.7 The Components of a Green Roof

The green roof consists of eight superimposed layers (1 to 8).

1. The load-bearing component of the roof
2. The moisture barrier
3. The thermal insulator
4. The waterproofing membrane (root barrier)
5. The drainage layer.
6. The filtering layer.
7. The growing medium (substrate)
8. The plant layer.

The green roof can be established on any load-bearing components (concrete, tanbark, wood). However, the choice of vegetated system must be suitable to load-bearing capacity of the building's roof. Drainage paths provide a way for excess water to reach rainwater drainage devices. The filter prevents any material from clogging between the growing medium and the drainage layer. Layers 4 to 8 form the green roof system. A water supply with a capacity appropriate for the size of the planted area must be provided on the roof to protect the plants in the case of a prolonged dry period.

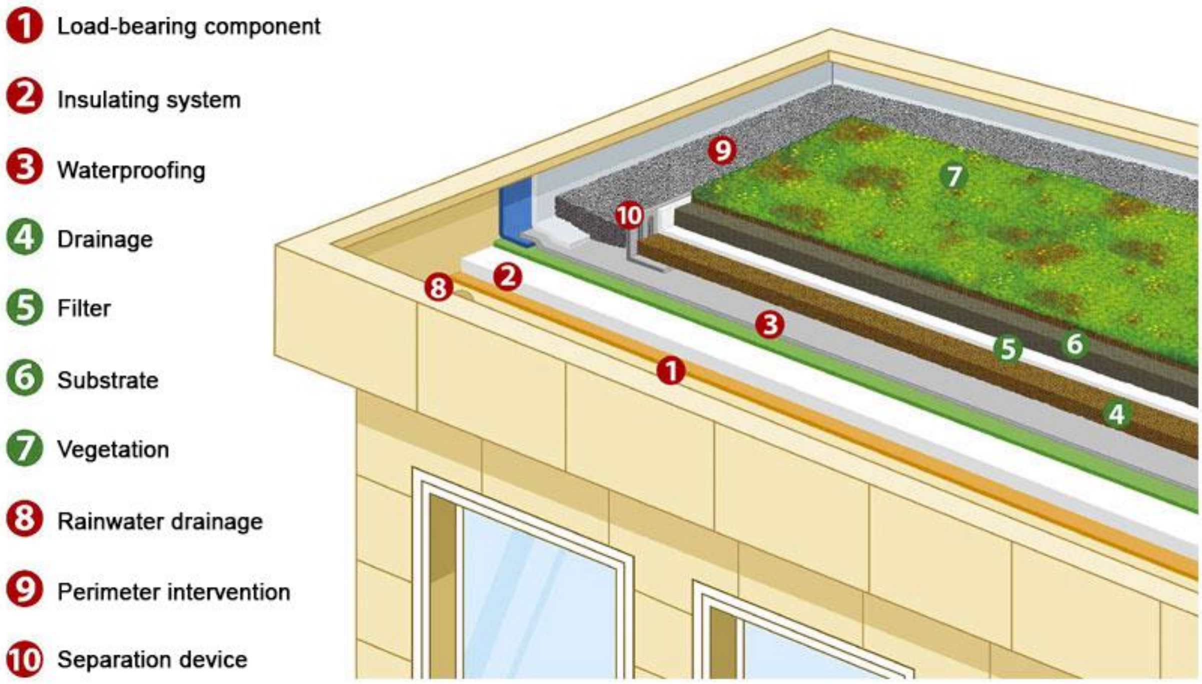


Fig. 12: components of green roof source : https://www.vegetalid.com/solutions/green-roofs/what-is-an-extensive-green-roof/concepts.html

3.3.8 Benefits of green roofs

As previously explained, the installation of green roofs offers a multitude of advantages, encompassing ecological, economic, and social benefits. They contribute to sustainable development, safeguard the environment, and enhance the biodiversity of urban spaces through nature-based solutions. Green roofs play a pivotal role in achieving sustainable urban design and development. The benefits of implementing green roofs are outlined in Table 8, and a more in-depth analysis will be conducted to foster a comprehensive comprehension of these advantages.

Table 8. Benefits of green roofs implementation in urban areas

Benefits	Findings
Environmental	• Natural filtration: green roofs act as natural air filtration by absorbing dust and cleaning air. • Stormwater management: green roofs work as porous surfaces that regulate stormwater runoff. • The process of photosynthesis in plants consumes CO_2 emissions and releases oxygen, keeping the air clean and lowering CO_2 dioxide emissions. • Up to 4% of heavy metal city dust could be trapped by green roofs. • Acoustics: green roofs have the potential to manage and minimize sound reflections. The noise level could be reduced by 8-10 db.
Economic	• Energy: green roofs provide the benefit of reduced energy use by shading, insulation, evapotranspiration, and greater thermal mass. • Green roofs reduce shrinkage and growth of building material due to temperature, in addition, they protect against UV rays and acid rain. • Thermal comfort: plants have a strong system influence to reduce the UHI, which is a major issue in cities and metropolitan regions due to its ability to absorb shortwave radiation and cool the atmosphere. • Green roofs are considered as UHI mitigation tools by reducing the ambient temperature from 0.3°C to 3°C. • Green roofs increase the service life of a building's roof by protecting it from temperature fluctuations, UV radiation fluctuations, and daily loads.
Social	• Green roofs provide rest and relaxation place as well as aesthetic appeal. • In addition, green roofs improve human health and well-being by exposing people to nature. • Plants relieve stress and reduce obesity by being close to green

	spaces; - Plants positively affect the people working or living nearby. According to the study, buildings with green spaces had higher staff productivity than those with less vibrant environments. • Compared to plants in gardens, plants in urban areas and sheds draw more attention. • Rooftops can offer essential circumstances for seasoned rare or endangered species.

Source: Abass et al., 2020 IOP Conf. Ser.: Mater. Sci. Eng. 713 012048

3.4 Living wall systems.

3.4.1 Definition of Living wall systems:

Living walls, also known as green walls or vertical gardens, are vertical structures intentionally covered with vegetation. They are typically attached to the exterior or interior walls of buildings and can be filled with a variety of plants, including flowers, herbs, vines, and mosses.

3.4.2 Green Facades and Urban Heat Island Phenomenon

Heat islands can impact communities by escalating peak energy demand during summertime, raising air conditioning expenses, raising levels of air pollution and greenhouse gas emissions, triggering heat-related illnesses and fatalities, and compromising water quality. These islands can emerge in both urban and rural settings.

In contrast, non-UHIs typically pose minimal risks to humans or the environment, a predictable outcome. Meanwhile, UHIs have received substantial attention over decades in urban areas characterized by diverse climates and landscapes.

The microclimate around towns is significantly influenced by impervious surfaces such as facades and streets, leading to elevated temperatures near buildings. This, in turn, contributes to discomfort and increased energy consumption for conditioning. A potential remedy for this issue is the adoption of vegetated roofs and facades, which utilize heat energy through evapo-transpiration. Moreover, these green installations aid in the vertical mixing of air, resulting in lower temperatures compared to the built surroundings. As warm air ascends over hard surfaces, it is replaced by cooler air, thereby mitigating the heat island effect. (Sheweka and Mohamed, 2012).

3.4.3 Thermal Impacts: shading and insulation.

The use of vegetation in vegetated facades serves as a solar radiation blocker, offering advantages over traditional materials like Meta-Plastic or metal. This is due to the vegetation not absorbing and radiating heat into the surrounding building. The effectiveness of this approach depends on foliage density. In a double-skin facade, temperatures in various layers are generally lower when plants are used instead of slats in the inner space. For the same solar radiation, the temperature increase is about half when using plants compared to slats. Installing plants in an internal double skin can reduce energy consumption in the conditioning system by up to 20%.

The physiological process in plants involves using a small portion of incident solar radiation for photosynthesis, while the rest contributes to water evaporation, regulating the plant's temperature. This results in effective solar radiation blocking without raising the plant's temperature. Vegetated facades offer shading benefits with aesthetic appeal and evaporative cooling. Despite requiring maintenance, they contribute to energy savings in buildings through natural shading (Sheweka and Mohamed, 2012).

in an experimental investigation (Fig.13) of the effect of shading buildings walls with plants, it shows that as more the non-shaded walls are more exposed to the thermal energy it results to the higher temperature of the wall surface. The energy absorbed will advance into the inner wall surfaces, resulting in elevation of the interior temperature. Consequently, when an air conditioning system is used to cool the room, more energy will be consumed (Fig. 14 &15)

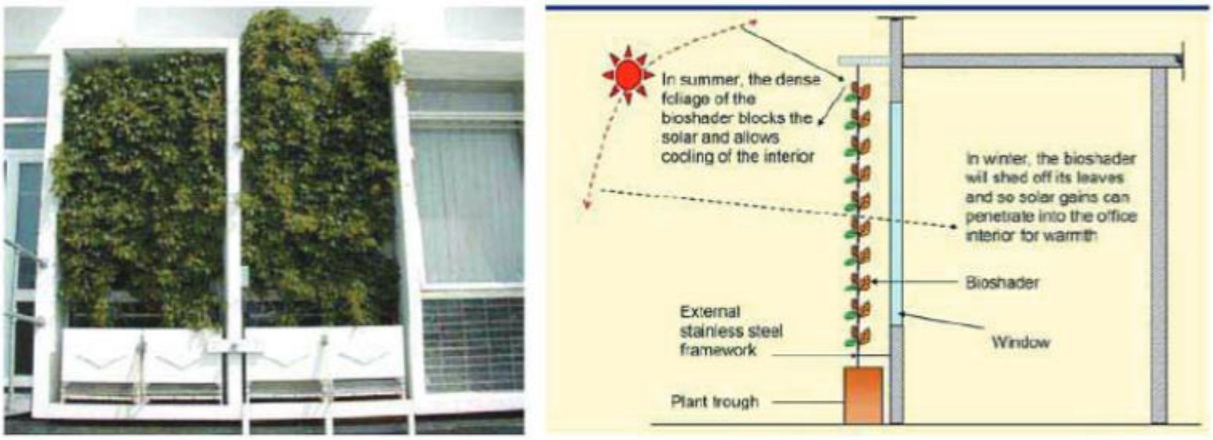


Fig.13: The Bio-shader experiment.

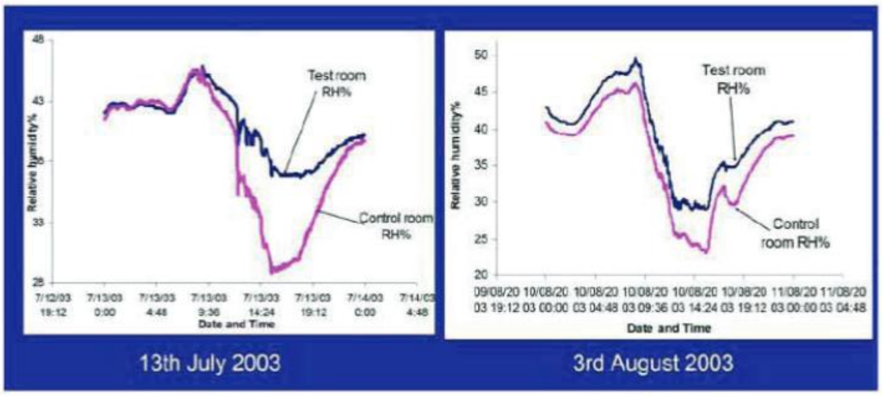


Fig. 14: The Bio-shader experiment (distribution of temperatures)

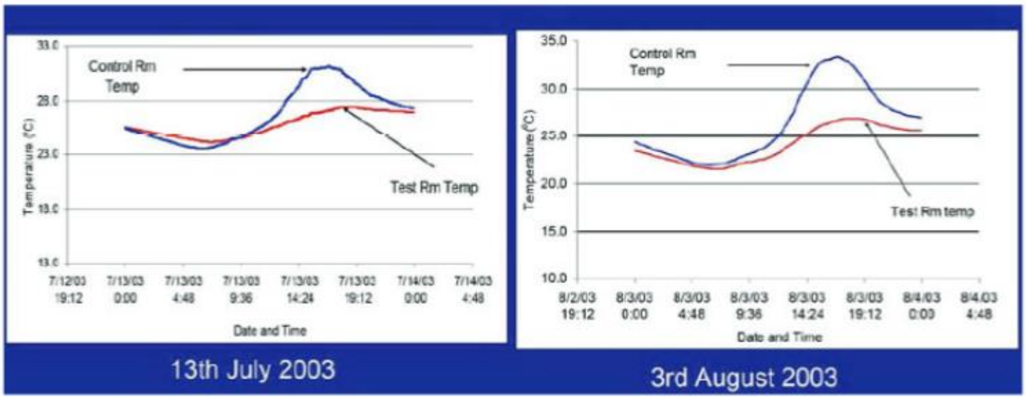


Fig. 15: The Bio-shader experiment (distribution of relative humidity)

3.4.4 Benefits of the green wall

There is an important potential of lowering urban temperatures when the building envelope is covered with vegetation, it can be concluded that the hotter and drier a climate is, the greater the effect of vegetation on urban temperatures. However, it has been pointed out that humid climates can also benefit from green surfaces, especially when both walls and roofs are covered with vegetation. As conclusion green facades benefits can be divided into two scales: public benefit scale and private benefits scale (Sheweka and Mohamed, 2012).

3.4.4.1 Green facades public benefits:

Table 9: Green Facades as a New Sustainable Approach Towards Climate Change

Area of Impact	**Description**	**Benefits**
Reduce Urban Heat Island Effect	The temperature increases in urban areas are caused by the replacement of natural vegetation with pavements, buildings, and other structures necessary to accommodate growing population. This results in the conversion of sunlight to heat. Vegetation cools buildings and the surrounding area through the processes of shading, reducing reflected heat, and evapotranspiration.	• Promotes natural cooling Processes. • Reduces ambient temperature in urban Areas. • Breaks vertical air flow which then cools the air as it slows down. • Shading surfaces/people
Improved Exterior Air Quality	Elevated temperatures in modern urban environments with increasing numbers of vehicles, air conditioners and industrial emissions have led toa rise in nitrogen oxides (NOx), sulfur oxides (SOx), volatile organic compounds (VOCs), carbon monoxide (CO) and particulate matter.	• Captures airborne pollutants and atmospheric deposition on leaf surfaces. • Filters noxious gases and particulate matter
Aesthetic Improvement	Green walls provide aesthetic variation in an environment in which people carry out their daily activities. Numerous studies have linked the presence of plants to improve human health and mental wellbeing.	• Creates visual interest-Hides / obscures unsightly features. • Increases property values. • Provides interesting freestanding structural elements, etc.

Source: Sheweka and Mohamed, 2012

3.4.4.2 Green facades private benefits:

Table 10: Green Facades as a New Sustainable Approach Towards Climate Change.

Area of Impact	Description	Benefits
Improved Energy Efficiency	Improves thermal insulation capacity through external temperature regulation. The extent of the savings depends on various factors such as climate, distance from sides of buildings, building envelope type, and density of plant coverage. This can impact both the cooling and heating	• Traps a layer of air within the plant mass. • Limits movement of heat through thick vegetation mass • Reduces ambient temperature via shading and plant processes of evapo-transpiration. • May create a buffer against the wind during the winter months. • Interior applications may reduce energy associated with heating and cooling outdoor air for indoor use
Building Structure Protection	Buildings are exposed to the weathering elements and overtime some of the organic construction materials may begin to break down, because of contraction and expansion shifts due to freeze-thaw cycles and UV exposure	• Protects exterior finishes from UV radiation, the elements, and temperature Fluctuations that wear down materials. • May benefit the seal or airtightness of doors, windows, and cladding by decreasing the effect of wind pressure.
Improved Indoor Air Quality	For interior projects, green walls can filter contaminates that are regularly flushed out of buildings through traditional ventilation systems. The filtration is performed by plants, and in the case of bio-filtration, micro-organisms	• Captures airborne pollutants such as dust and pollen. • Filters noxious gases VOC's from carpets, furniture and other building elements
Noise Reduction	• The growing media in living wall systems will contribute to reduction of sound levels that transmit through or reflect from the living wall system. Factors that influence noise reduction includes the depth of the growing media, the materials used as structural components of the living wall system, and the overall coverage.	
LEED	• Green walls contribute directly to achieving credits, or contribute to earning credits when used with other sustainable building elements	
Marketing	• Improved aesthetics may help to market a project and provide valuable amenity space	

Source: Sheweka and Mohamed, 2012.

4 Methodology.

4.1 Introduction to the case study – Cairo, Egypt

Cairo is the capital of Egypt is located at latitudes 29^{O} 45′ N − 30^{O} 16′ N and longitude 30^{O} 58′ E − 31^{O} 25′ E (Fig.16) and it represents the 6th largest metropolitan area in the world and the largest urban area in Africa, the Arab world and middle east (Forstall et al.,2004) Cairo's urban sprawl has been expanded until it has been merged with another two States which are (Giza and Qalubia) to form one big state called the Greater Cairo

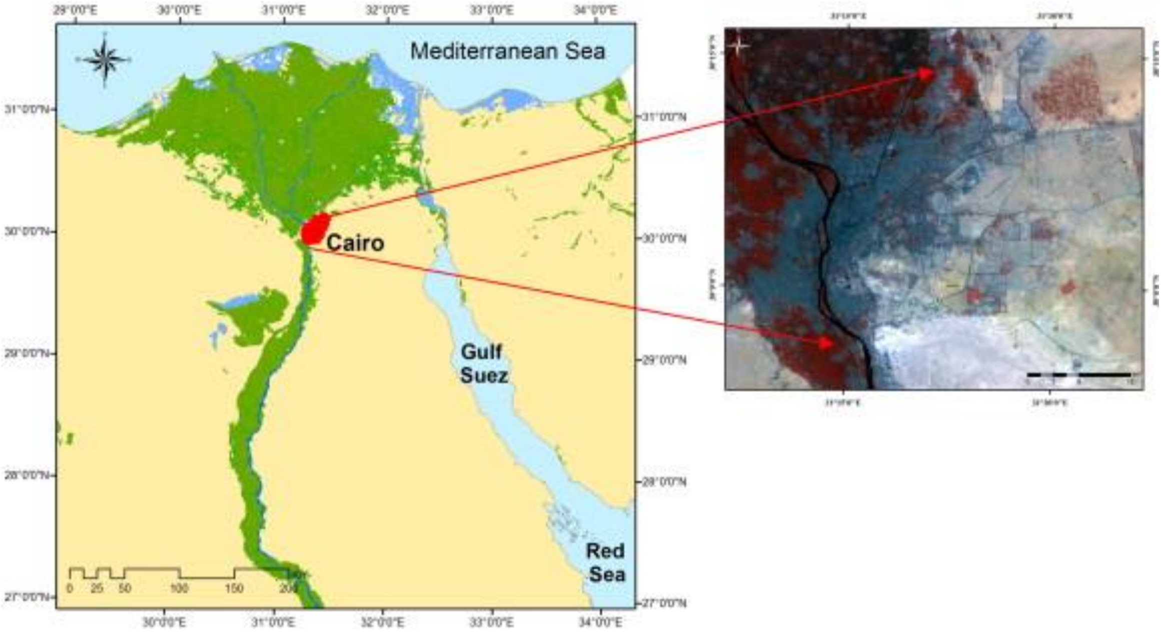


Fig.16. (a) Location of Cairo city. (b) Cairo city in 2007, source: (Effat & Hassan, 2014)

Climatologically, Cairo lies in the sub-tropical climatic region during the transitional seasons Spring (May–March) and Autumn (September–November), hot desert depressions known as Khamasin depressions occur. These are often associated with hot dry wind. In Winter (December–February), the climate is cold, moist with few rainy days. In Summer (June–August), Cairo's climate is hot, dry, and rainless (Effat & Hassan, 2014).

4.1.1 Land use and Land Cover (LULC)change.

The doubling of the population that occurred over the last three decades has led to an inordinate change in LULC.

The Landsat images analysis reveals that the built-up area increased from 21.4% in 1986 and reached 35% in 2017 (Fig.17) (Abd-Elmabod et al., 2022).

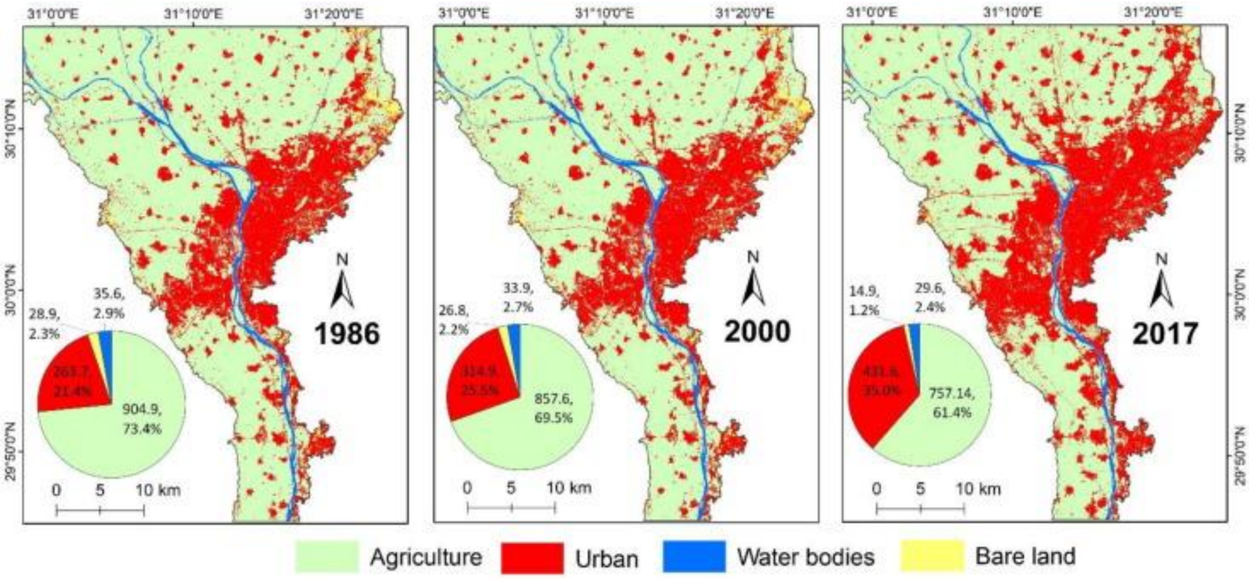


Fig. 17. LULC in Greater Cairo over a thirty-year period (1986, 2000, and 2017) adapted from (Abd-Elmabod et al., 2022).

Much of the recent development has taken the form of spontaneous, informal built-up areas, which became widely spread after the 2011 Egyptian revolution. Recently, the Egyptian government implemented new and restrictive regulations to limit the destruction of the agricultural areas. Fig. 18 displays ground photos depicting the major land use and land cover (LULC) types in Cairo, including cultivated land, informal built-up areas, formal urban areas, roads, and the river Nile. The results revealed that vegetated land accounted for 73.4% of the total area in 1986, decreasing by 3.9% over 14 years until 2000, and further declining by 8.1% from 2000 to 2017 (Abd-Elmabod et al., 2022).

Fig. 18. Ground photos for the major LULC classes in grater Cairo. a) cultivated land; b) informal built-up areas; c) formal urban and roads; d) river Nile adapted from (Abd-Elmabod et al., 2022).

Previous studies from Abd-Elmabod et al., 2022 have revealed a significant rise in Land Surface Temperature (LST) across Cairo. The increase in surface temprature are slightly more pronounced in heavily urbanized regions compared to cooler areas such as agriculture and water bodies. The introduction of roads into agricultural land could expedite urbanization, subsequently intensifying Urban Heat Island (UHI) effects. UHI, in turn, may induce climate change, alter evapotranspiration rates, and lead to changes in Land Use and Land Cover (LULC). The substantial expansion of informal settlements has notably contributed to a significant elevation in land surface temperature (Abd-Elmabod et al., 2022).

4.2 Methodology outline

This chapter aims to explore the impact of green roofs on diminishing air temperature within outdoor spaces at a height of 1.80 m from the ground and the resultant energy savings for cooling buildings in diverse-density built-up areas of Cairo. The case studies are segregated into two distinct groups.

I have chosen 3 locations to apply my assessment on and my criteria that I wanted an example for an official formal type of urban form and lower-class type of urban form, and I chose them because I have visited them and there is a huge difference in the urban quality between Imbaba and Uptown Cairo.

The chosen locations of study will assess the benefit of green roofs on lowering air temperature at the pedestrian level (1.80 m from the ground) and conserving cooling energy within buildings in three areas with different aspect ratios but uniform building heights. This group comprises Uptown Cairo and two locations in Imbaba, all featuring the same building heights (12 m) and distinct aspect ratios (H/W = 1, 2, and 3, respectively).

The simulation of each area was executed in ENVI-met v.4, comparing the reference case (conventional roof), extensive green roofs, and intensive green roofs. Outputs from ENVI-met, encompassing air temperature, wind speed, and relative humidity, were analyzed to ascertain which green roof type exhibits the most effective air temperature reduction at the pedestrian level (1.80 m from the ground) in each area. Additionally, physiological equivalent temperature (PET) was computed using ENVI-met at 1.80 m from the ground to identify the optimal green roof type for enhancing outdoor thermal comfort. Fig.19 illustrates the methodology framework in a flowchart format.

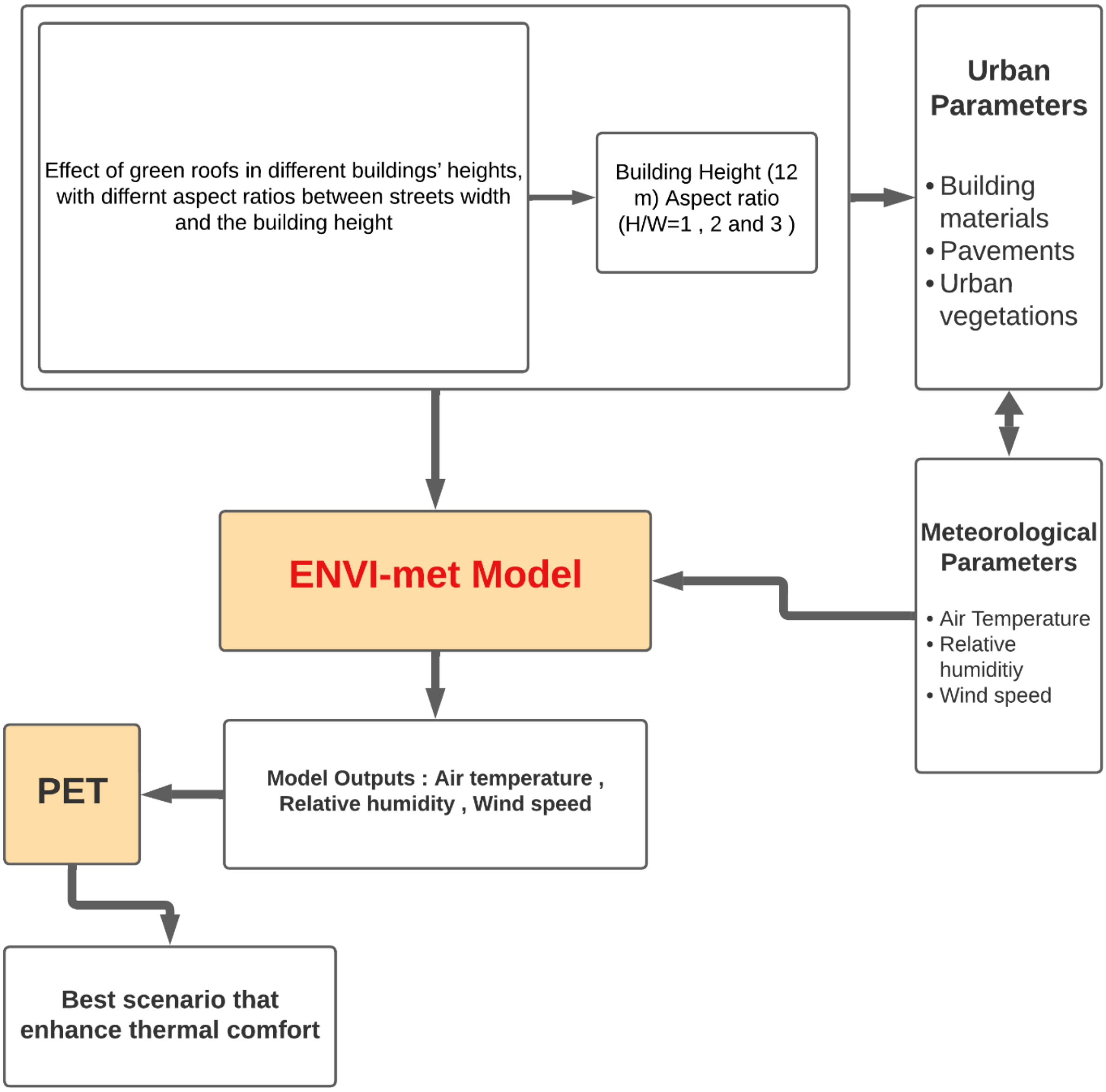


Fig. 19. Methodology framework.

4.3 Simulation tools

This chapter utilized the ENVI-met modeling program, specifically ENVI-met v.4.0, which is a comprehensive three-dimensional model designed for simulating the interactions among built-up areas, urban vegetation, and the atmosphere. The model operates on a grid basis, featuring horizontal resolutions ranging from 0.5 to 10 m and a temporal scope of 24-48 h. Operating on an energy balance approach, ENVI-met can effectively model the energy exchange processes between vegetation and adjacent surfaces. The program represents plants as dynamic entities interacting with the local environment through naturally occurring processes such as evapotranspiration, thereby reducing the latent heat flux. This capability is particularly advantageous for this study, as it enables a detailed understanding of the interplay between plants and the surrounding air with a high degree of accuracy. Additionally, ENVI-met can estimate the reduction in reflected shortwave radiation resulting from the shading provided by vegetation. The model is proficient in calculating various radiant energy components, including shortwave radiation, latent heat flux, and longwave radiation.

ENVI-met has been widely applied in diverse studies investigating the correlation between urban configurations and mitigation strategies, such as the presence of trees, water bodies, wall and paving materials, and green roofs. Many of these studies have focused on a 24-hour cycle, taking into consideration meteorological parameters like wind speed, relative humidity, air temperature, and heat fluxes. The latest version of the model has the capability to use full forcing, allowing for the consideration of meteorological parameters on an hourly basis. Furthermore, the model can compute the Physiological Equivalent Temperature (PET) to illustrate the impact on thermal comfort using Biomet.

The residential micro-urban area was simulated in ENVI-met v.4 using urban parameters such as canyons' aspect ratio, canyons' paving materials and albedo, and building heights. The model used the forcing option with hourly meteorological data. The model domain size was 100 m × 100 m × 60 m with resolution of 2.0 m × 2.0 m × 0.8 m. To ensure model accuracy, additional nesting grids were added to the model to increase the authenticity of the simulation results and reduce numerical problems that could be caused by model borders affecting internal model dynamics. Furthermore, the grid structure of the model successfully passed the ENVI-met check beforehand. Therefore, the model used an additional ten grid cells on each model's border to minimize the turbulence and avoid overall model problems later.

Table 11 shows the ENVI-met model settings, urban characteristics of the urban area used for the model validation, and the design of green roofs. The LEONARDO tool was used to export the simulated air temperature, relative humidity, and wind speed by calculating the average data of the whole domain at 1.80 m from the ground.

Table 11. ENVI-met model settings and the urban parameters of the validated area.

Urban parameters			
Urban density	60%	Sidewalk paving albedo	0.55
Streets aspect ratio (H/W)	1, 2 and 3	Building heights	12 m
Vegetation ratio	0%	Street materials	Asphalt
Buildings albedo	0.35	Building materials	Red bricks and concrete
ENVI-met settings			
Simulation day	24.08.2023 – 25.08.2023	Simulation start time	00.00 h–24 August
Simulation end time	5.00 h–25 August	Simulation period	30 h
Wind speed at 10 m above ground (m/s)	2.8	Min. and max. air temperature (°C)	23.00 min.–35.00 max. Source: Cairo EPW file
Location	Cairo, Egypt	Wind direction (0 = from north, °)	315
Model domain area (m)	100 × 100 × 60	Spatial resolution (m)	2.00 × 2.00 × 0.80
Model rotation, (°)	0.00 – north	Nesting grids (m)	20
Green roof design			
Extensive green roof		Intensive green roof	
LAD	0.3	LAD	2.5
Soil thickness (cm)	20	Soil thickness (cm)	70
Height of plants (cm)	50	Height of plants (cm)	200
Root depth (cm)	20	Root depth (cm)	50–70
Roof U-value (W/m^2K)	0.5	Roof U-value (W/m^2K)	0.3
Plants albedo	0.25		

4.3.1 Case study areas.

Cairo experiences summer air temperatures ranging from 25 to 40 °C. Positioned at latitude 30.06 and longitude 31.25, the city has a varied range of urban densities, spanning from 25% in meticulously planned districts to 85% in informal settlements. Additionally, Cairo exhibits diverse aspect ratios and urban densities, factors intricately linked to the area's age and the economic status of its residents.

The study zones (Map 1) encompass Uptown Cairo, which is a luxurious and well-planned residential compound, and two areas in Imbaba, representing informal, high-density residential spaces. These regions share a uniform building height of 12 m but differ in aspect ratios (H/W) of 1, 2, and 3, respectively. The figures (20,21,22) illustrate the distinctions among the investigated micro-urban areas in Cairo, along with cross-sections demonstrating each area's characteristics.

Map 1, Shows the locations selected in Cairo. Source: Google earth

Fig.20 Uptown Cairo (H/W=1) Building Height 12m Source: Google earth

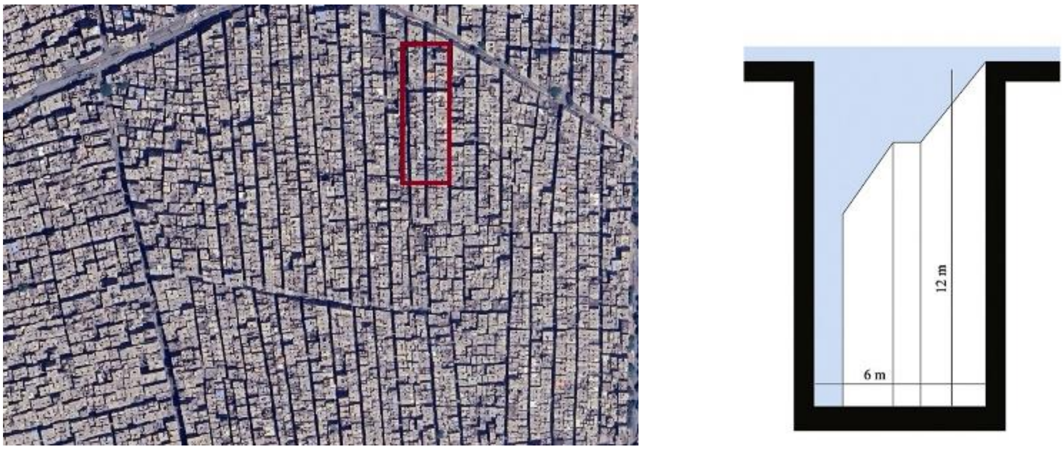


Fig.21 Imbaba – Aspect ratio (H/W=2) building height 12 m street width 6m Source: Google earth

Fig.22 Imbaba – Aspect ratio (H/W=3) building height 12 m street width 4m Source: Google earth

4.3.2 Design Scenarios.

Various previous studies have revealed that an increase in soil depth and plant leaf density led to greater air temperature reduction. This effect can be related to the leaf density and soil moisture that reduce surface temperature and absorb solar radiation. The previous results confirmed that intensive green roofs could positively reduce energy demand (Vera et al., 2015, Sailor et al., 2012). There are differences between extensive and intensive green roofs. The intensive green roof involves high maintenance, periodic irrigation, and moderately high costs. However, different studies recommended using extensive green roofs due to their feasibility, low maintenance costs, and minimal irrigation demands (Razzaghmanesh et al., 2014).

The green roof scenarios examined in this study were made by considering their type design, weight loads, construction, and maintenance costs. Firstly, this simulation evaluated the extensive green roof with soil substrates of 20 cm and a plant height of 50 cm. The second scenario was the intensive green roof with soil substrates of 70 cm and a plant height of 2 m. Both green roof types had eight layers. Fig.23 shows the typical design of the traditional roof and the green roofs developed by adding a waterproof layer, drainage layer, filter layer, soil, and vegetation layer.

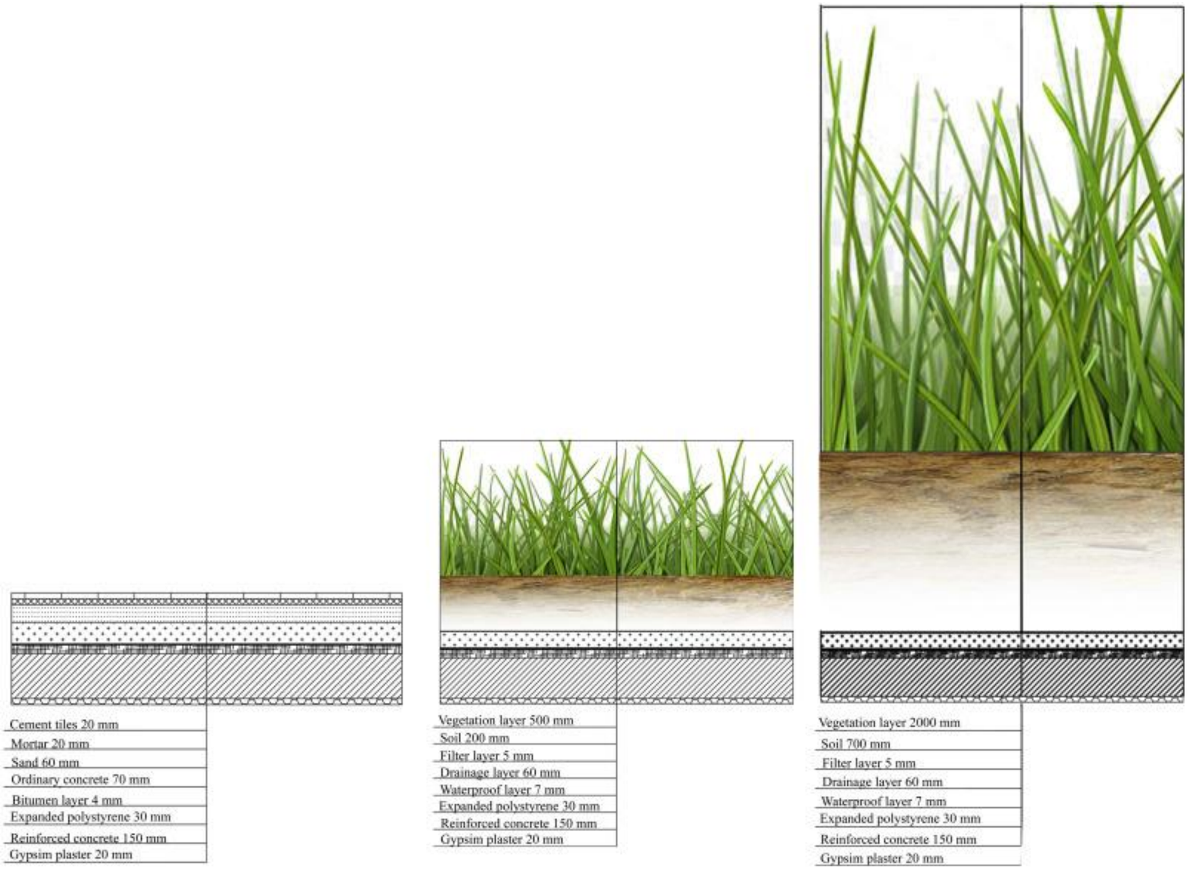
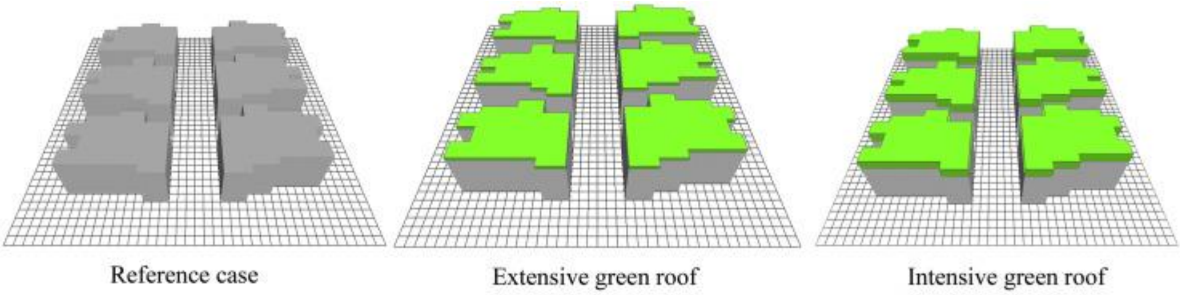
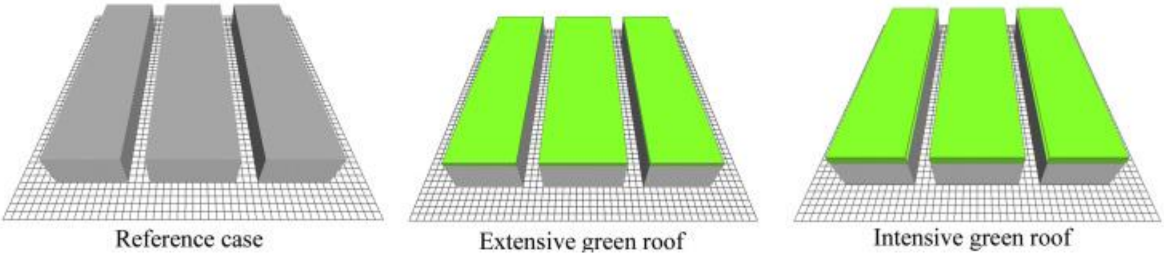


Fig. 23. Traditional roof, extensive green roof and intensive green roof, respectively.

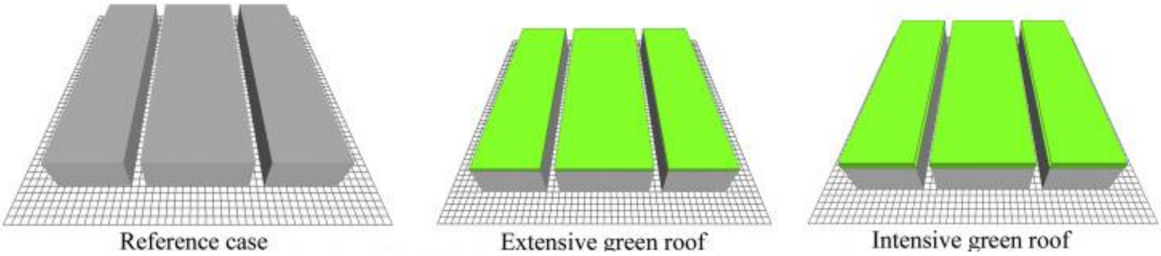
The additional loads of the green roofs could be considered reliable because the total loads of the residential building roofs are up to 690 kg/m2 (Anan, 2004). Both green types were evaluated in two groups, with each group having three areas. The three areas have the same building heights and different street aspect ratios, as shown in Fig.24. Both green roofs were applied above the buildings of the two groups to investigate their effect on air temperature at the pedestrian level (1.80 m from the ground). A total of 9 models were run.


Reference case Extensive green roof Intensive green roof

Building Height 12 m, street width 12 m, H/W = 1 – Uptown Cairo


Reference case Extensive green roof Intensive green roof

Building Height 12 m, street width 6 m, H/W = 2 – Imbaba


Reference case Extensive green roof Intensive green roof

Building Height 12 m, street width 4 m, H/W = 3 – Imbaba

Fig. 24 ENVI-met model of the various green roof types same building heights and different aspect ratios.

source: Author

5. Results

5.1 Air temperature

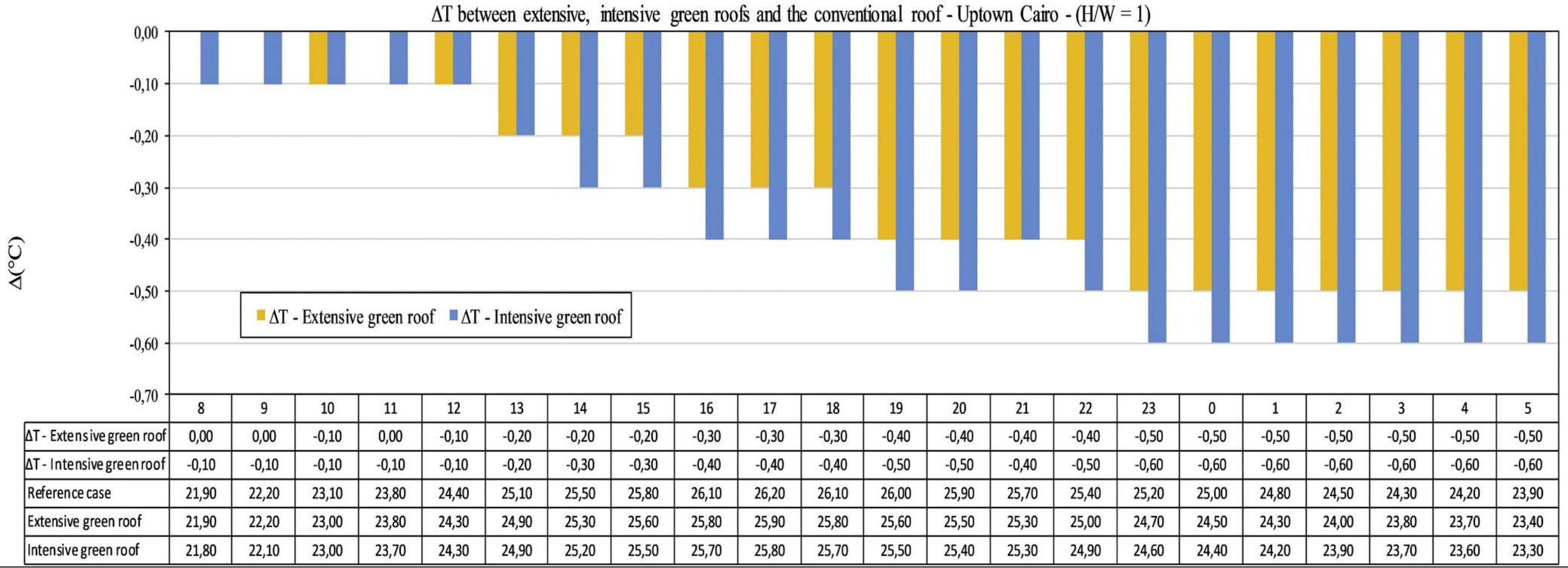
The simulation was focused on three areas in Cairo - Uptown Cairo and two regions in Imbaba. These areas have the same building height of 12 m but differ in aspect ratios (H/W = 1, 2, and 3, respectively). I investigated the influence of green roofs on air temperature in these three locations with the same building heights yet different aspect ratios.

Air temperature results were measured by the software considering the average throughout the entire study area at a height of 1.80 m. The results indicate that both extensive and intensive green roofs lead to maximum reductions in outdoor air temperature in Imbaba (H/W = 3), reaching up to 1.7 K and 2.0 K, respectively. Similarly, in Imbaba (H/W = 2), extensive and intensive green roofs contribute to air temperature reductions of up to 1.4 K and 1.6 K, respectively, as shown in Tables 12, 13 and 14. The tables show the difference in the air temperature between the conventional roof case, the extensive and extensive green roofs during the simulation time.

Obviously, both types of green roofs exhibit a more limited impact on air temperature reduction in Uptown Cairo, characterized by an aspect ratio of H/W = 1, compared to the other aspect ratios.

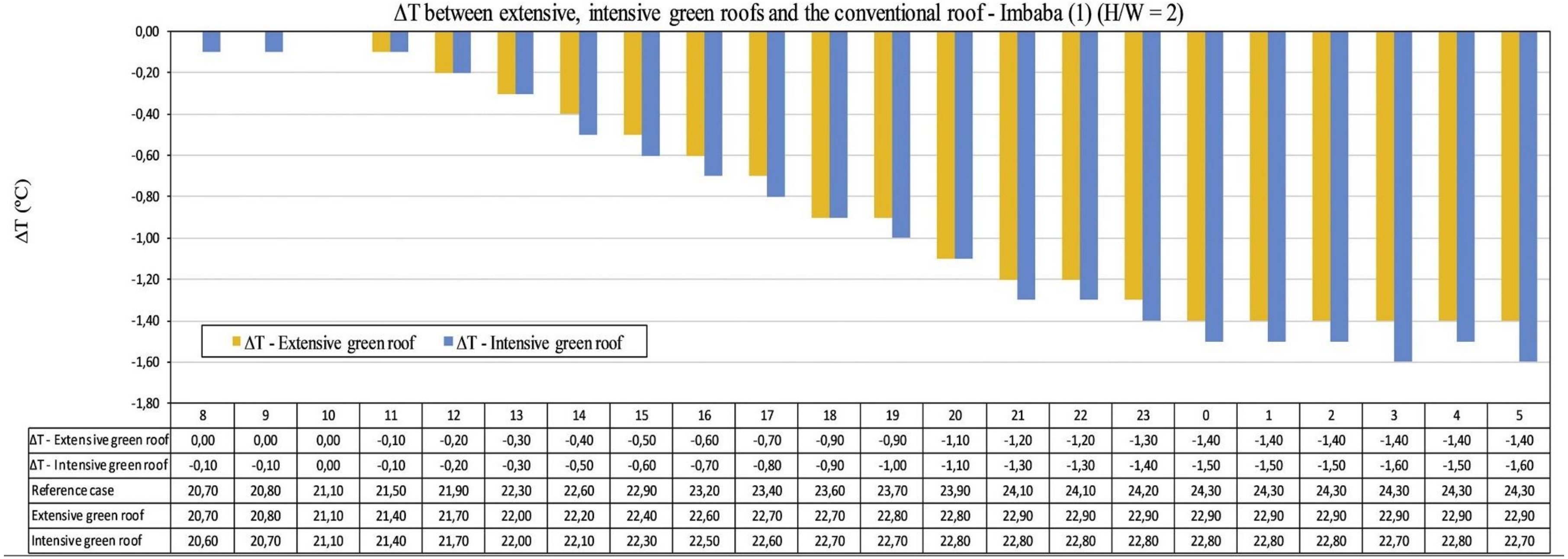
Consequently, extensive, and intensive green roofs are considered as powerful strategies suitable to be applied in areas with aspect ratios of H/W = 3 and 2, both possessing building heights of 12 m. This application effectively reduces outdoor air temperature.

Fig.26 illustrates the thermal maps of the three locations at 3:00 pm that are resulted from the simulation software, highlighting the achieved reduction in air temperature through the implementation of green roofs as shown In the Figure 26 that there are differences in the colors that represent the air temperature around the buildings resulted from the existence of the green roofs.



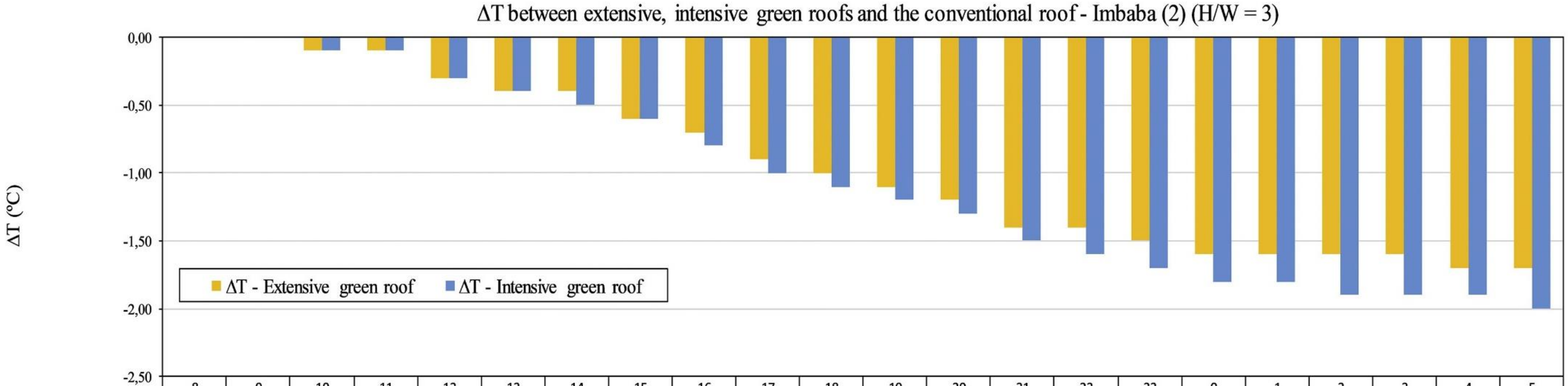
	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5
ΔT - Extensive green roof	0,00	0,00	-0,10	0,00	-0,10	-0,20	-0,20	-0,20	-0,30	-0,30	-0,30	-0,40	-0,40	-0,40	-0,40	-0,50	-0,50	-0,50	-0,50	-0,50	-0,50	-0,50
ΔT - Intensive green roof	-0,10	-0,10	-0,10	-0,10	-0,10	-0,20	-0,30	-0,30	-0,40	-0,40	-0,40	-0,50	-0,50	-0,40	-0,50	-0,60	-0,60	-0,60	-0,60	-0,60	-0,60	-0,60
Reference case	21,90	22,20	23,10	23,80	24,40	25,10	25,50	25,80	26,10	26,20	26,10	26,00	25,90	25,70	25,40	25,20	25,00	24,80	24,50	24,30	24,20	23,90
Extensive green roof	21,90	22,20	23,00	23,80	24,30	24,90	25,30	25,60	25,80	25,90	25,80	25,60	25,50	25,30	25,00	24,70	24,50	24,30	24,00	23,80	23,70	23,40
Intensive green roof	21,80	22,10	23,00	23,70	24,30	24,90	25,20	25,50	25,70	25,80	25,70	25,50	25,40	25,30	24,90	24,60	24,40	24,20	23,90	23,70	23,60	23,30

Table 12. Air temperature of the 1st area -reference case, extensive and intensive green roofs
ΔT = green roof scenario – reference case as resulted from the simulation



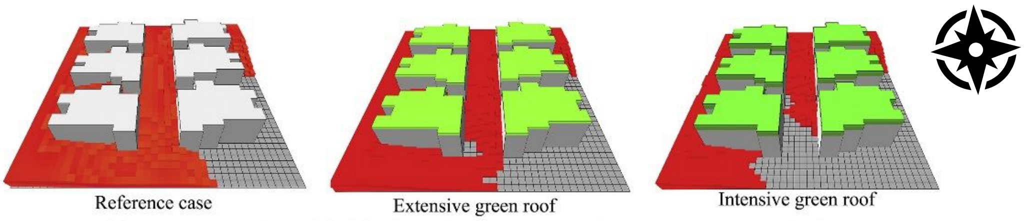
	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5
ΔT - Extensive green roof	0,00	0,00	0,00	-0,10	-0,20	-0,30	-0,40	-0,50	-0,60	-0,70	-0,90	-0,90	-1,10	-1,20	-1,20	-1,30	-1,40	-1,40	-1,40	-1,40	-1,40	-1,40
ΔT - Intensive green roof	-0,10	-0,10	0,00	-0,10	-0,20	-0,30	-0,50	-0,60	-0,70	-0,80	-0,90	-1,00	-1,10	-1,30	-1,30	-1,40	-1,50	-1,50	-1,50	-1,60	-1,50	-1,60
Reference case	20,70	20,80	21,10	21,50	21,90	22,30	22,60	22,90	23,20	23,40	23,60	23,70	23,90	24,10	24,10	24,20	24,30	24,30	24,30	24,30	24,30	24,30
Extensive green roof	20,70	20,80	21,10	21,40	21,70	22,00	22,20	22,40	22,60	22,70	22,70	22,80	22,80	22,90	22,90	22,90	22,90	22,90	22,90	22,90	22,90	22,90
Intensive green roof	20,60	20,70	21,10	21,40	21,70	22,00	22,10	22,30	22,50	22,60	22,70	22,70	22,80	22,80	22,80	22,80	22,80	22,80	22,80	22,70	22,80	22,70

Table 13. Air temperature of the 2^{nd} area -reference case, extensive and intensive green roofs
ΔT = green roof scenario – reference case as resulted from the simulation



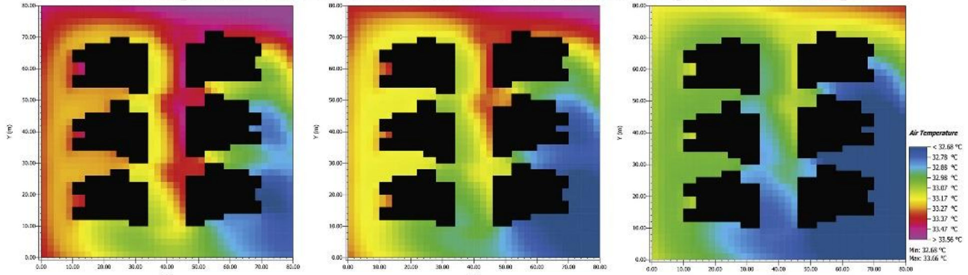
	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5
ΔT - Extensive green roof	0,00	0,00	-0,10	-0,10	-0,30	-0,40	-0,40	-0,60	-0,70	-0,90	-1,00	-1,10	-1,20	-1,40	-1,40	-1,50	-1,60	-1,60	-1,60	-1,60	-1,70	-1,70
ΔT - Intensive green roof	0,00	0,00	-0,10	-0,10	-0,30	-0,40	-0,50	-0,60	-0,80	-1,00	-1,10	-1,20	-1,30	-1,50	-1,60	-1,70	-1,80	-1,80	-1,90	-1,90	-1,90	-2,00
Reference case	20,40	20,50	20,80	21,00	21,40	21,70	21,90	22,20	22,50	22,80	23,00	23,20	23,40	23,70	23,80	23,90	24,10	24,10	24,20	24,20	24,30	24,30
Extensive green roof	20,40	20,50	20,70	20,90	21,10	21,30	21,50	21,60	21,80	21,90	22,00	22,10	22,20	22,30	22,40	22,40	22,50	22,50	22,60	22,60	22,60	22,60
Intensive green roof	20,40	20,50	20,70	20,90	21,10	21,30	21,40	21,60	21,70	21,80	21,90	22,00	22,10	22,20	22,20	22,20	22,30	22,30	22,30	22,30	22,40	22,30

Table 14. Air temperature of the 3rd area -reference case, extensive and intensive green roofs
ΔT = green roof scenario – reference case as resulted from the simulation



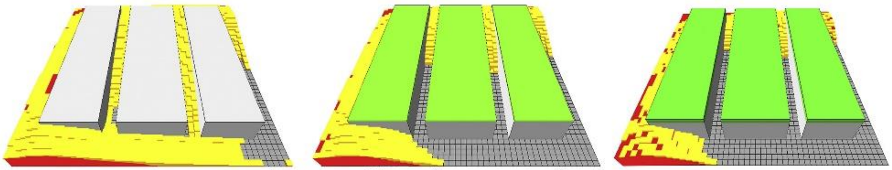
Reference case Extensive green roof Intensive green roof

Air temperature above 33 C in the reference case and the two green roofs - 3.00 pm



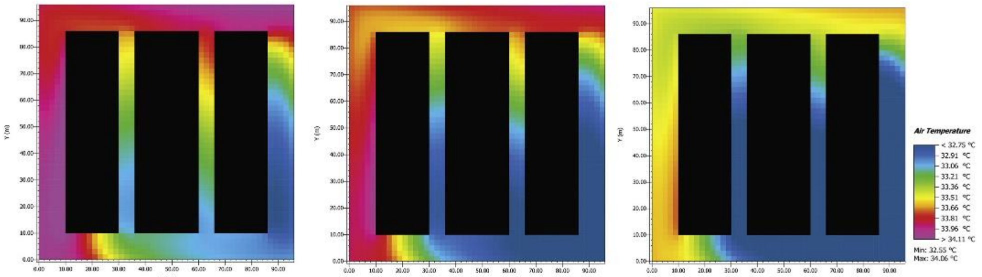
Reference case Extensive green roof Intensive green roof

Air temperature maps at 3.00 pm - Uptown Cairo - Aspect ratio (H/W = 1)



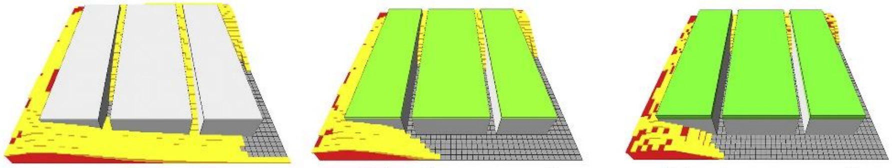
Reference case Extensive green roof

Air temperature above 33 C in the reference case and the two green roofs - 3.00 pm



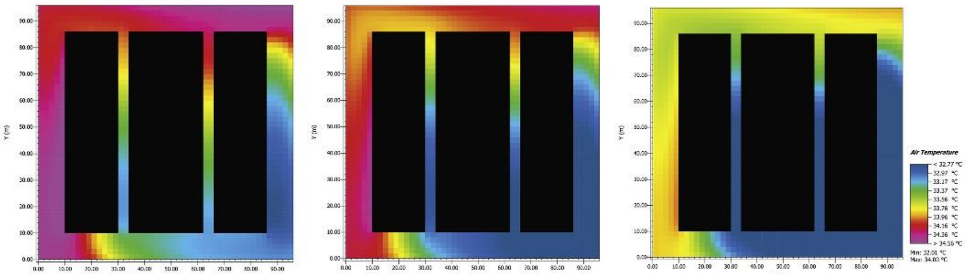
Reference case Extensive green roof Intensive green roof

Air temperature maps at 3.00 pm - Imbaba - Aspect ratio (H/W = 2)



Reference case Extensive green roof Intensive green roof

Air temperature above 33 C in the reference case and the two green roofs - 3.00 pm



Reference case Extensive green roof Intensive green roof

Air temperature maps at 3.00 pm - Imbaba - Aspect ratio (H/W = 3)

Fig. 26: Thermal maps of the three locations and comparison between the reference case and green roof scenario at 3:00 pm the difference in the color diagram represents the difference of the air temperature. Source: Author

The results indicate that green roofs have the most significant impact on outdoor air temperature in densely constructed areas characterized by deep canyons. This is caused by the expansive surface area of roofs within high-density regions, which, in comparison to low-density built-up areas, offers more horizontal spaces for urban vegetation.

Fig.27 illustrates the extensive horizontal green spaces achieved by implementing green roofs in these densely built-up areas.

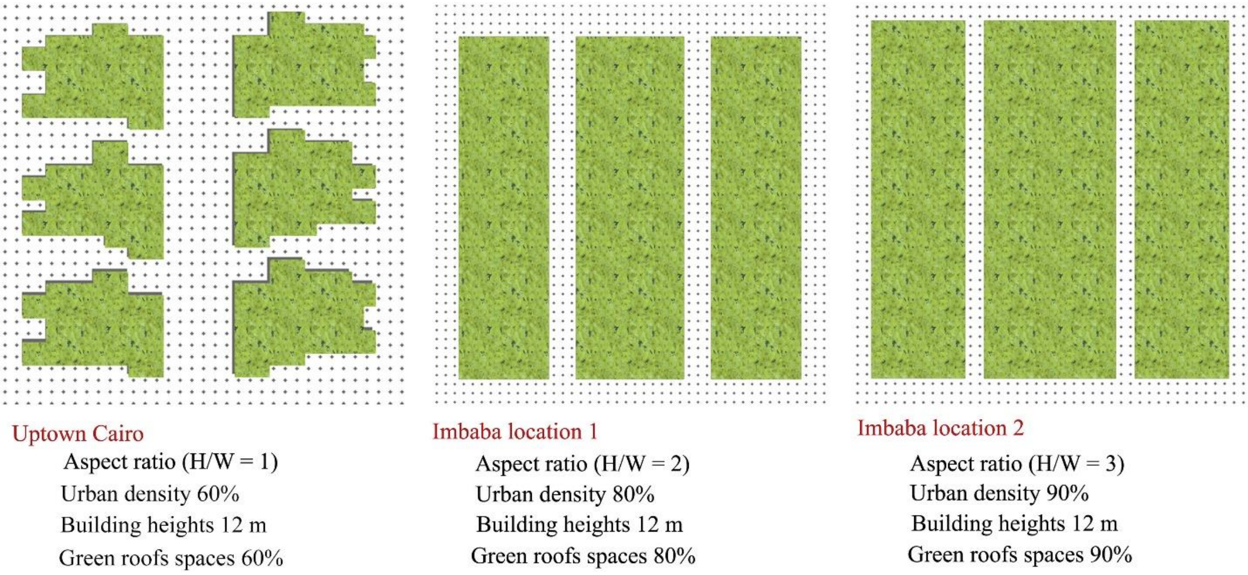
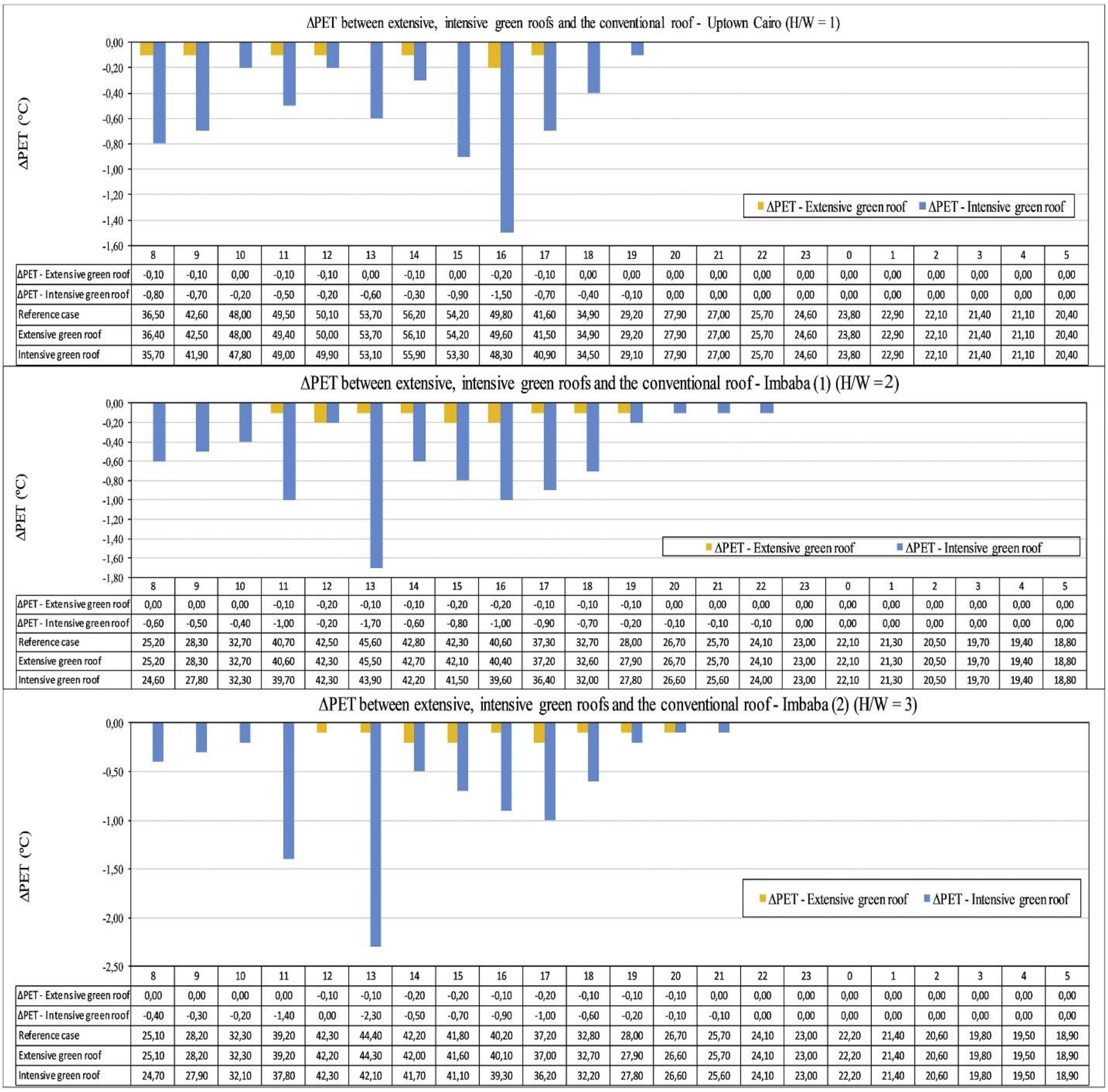


Fig.27. Comparison of the density in the three areas and its effect on providing more horizontal spaces for green roofs.

5.2 Physiological equivalent temperature (PET)

PET calculations were conducted by averaging across the entire study area at a height of 1.80 m (the average height of pedestrians). The outcomes reveal that extensive green roofs marginally reduce PET by 0.1- 0.2 K across the three areas. In contrast, intensive green roofs exhibit a substantial impact on PET, achieving a maximum reduction of 1.5 K in Uptown Cairo (H/W = 1). Additionally, the intensive type decreases PET in the other two areas (H/W = 2 and 3) by 1 K and 0.9 K, respectively (Table 15). Consequently, the urban density directly influences how green roofs affect PET enhancement. This suggests that intensive green roofs can effectively diminish PET and improve thermal comfort in areas characterized by buildings of 12 m in height and aspect ratios of H/W = 1, 2, and 3.



	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5
ΔPET - Extensive green roof	-0,10	-0,10	0,00	-0,10	-0,10	0,00	-0,10	0,00	-0,20	-0,10	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
ΔPET - Intensive green roof	-0,80	-0,70	-0,20	-0,50	-0,20	-0,60	-0,30	-0,90	-1,50	-0,70	-0,40	-0,10	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Reference case	36,50	42,60	48,00	49,50	50,10	53,70	56,20	54,20	49,80	41,60	34,90	29,20	27,90	27,00	25,70	24,60	23,80	22,90	22,10	21,40	21,10	20,40
Extensive green roof	36,40	42,50	48,00	49,40	50,00	53,70	56,10	54,20	49,60	41,50	34,90	29,20	27,90	27,00	25,70	24,60	23,80	22,90	22,10	21,40	21,10	20,40
Intensive green roof	35,70	41,90	47,80	49,00	49,90	53,10	55,90	53,30	48,30	40,90	34,50	29,10	27,90	27,00	25,70	24,60	23,80	22,90	22,10	21,40	21,10	20,40

	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5
ΔPET - Extensive green roof	0,00	0,00	0,00	-0,10	-0,20	-0,10	-0,10	-0,20	-0,20	-0,10	-0,10	-0,10	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
ΔPET - Intensive green roof	-0,60	-0,50	-0,40	-1,00	-0,20	-1,70	-0,60	-0,80	-1,00	-0,90	-0,70	-0,20	-0,10	-0,10	-0,10	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Reference case	25,20	28,30	32,70	40,70	42,50	45,60	42,80	42,30	40,60	37,30	32,70	28,00	26,70	25,70	24,10	23,00	22,10	21,30	20,50	19,70	19,40	18,80
Extensive green roof	25,20	28,30	32,70	40,60	42,30	45,50	42,70	42,10	40,40	37,20	32,60	27,90	26,70	25,70	24,10	23,00	22,10	21,30	20,50	19,70	19,40	18,80
Intensive green roof	24,60	27,80	32,30	39,70	42,30	43,90	42,20	41,50	39,60	36,40	32,00	27,80	26,60	25,60	24,00	23,00	22,10	21,30	20,50	19,70	19,40	18,80

	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5
ΔPET - Extensive green roof	0,00	0,00	0,00	0,00	-0,10	-0,10	-0,20	-0,20	-0,10	-0,20	-0,10	-0,10	-0,10	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
ΔPET - Intensive green roof	-0,40	-0,30	-0,20	-1,40	0,00	-2,30	-0,50	-0,70	-0,90	-1,00	-0,60	-0,20	-0,10	-0,10	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Reference case	25,10	28,20	32,30	39,20	42,30	44,40	42,20	41,80	40,20	37,20	32,80	28,00	26,70	25,70	24,10	23,00	22,20	21,40	20,60	19,80	19,50	18,90
Extensive green roof	25,10	28,20	32,30	39,20	42,20	44,30	42,00	41,60	40,10	37,00	32,70	27,90	26,60	25,70	24,10	23,00	22,20	21,40	20,60	19,80	19,50	18,90
Intensive green roof	24,70	27,90	32,10	37,80	42,30	42,10	41,70	41,10	39,30	36,20	32,20	27,80	26,60	25,60	24,10	23,00	22,20	21,40	20,60	19,80	19,50	18,90

Table 15. the effect of green roofs on PET in areas with the same building height and different aspect ratios - ΔPET = green roof scenario – reference case. The effect of intensive green roofs on PET is higher than the effect of the extensive one.

These results show the role that green roofs can play in achieving the best impact on the air temperature which can mitigate the effect of UHIs in dense cities as Cairo also it will play a pivotal role to decrease the heat inside homes as most of the roofs of this informal residential area like Imbaba are not isolated from heat.

6. Discussion

The metropolis of Cairo is overpopulated, has very dense built-up areas, and has been undergone to a continuous desertification due to street expansions and building new bridges to solve the traffic problems Fig.28. Which also affects the quality of life of the residents and increases the UHI effect in Cairo. This study aimed to investigate the effect of using the two types of green roofs in different urban densities to lower the outdoor air temperature. Moreover, outdoor thermal comfort was discussed by calculating PET.

Fig. 28. Sample of the desertification that has been done over the years in Heliopolis city.

This study showed that green roofs could reduce air temperature at pedestrian level (1.80 m from the ground) by 0.1–2.0 K. Furthermore, the green roof effect on reduction of air temperature at the pedestrian level is closely related to building height. The maximum effect of green roofs on air temperature reduction in densely constructed areas characterized by deep canyons.

In addition, the results indicate that extensive and intensive green roofs lead to maximum reductions in outdoor air temperature in Imbaba (H/W = 3), reaching up to 1.7 K and 2.0 K, respectively. Similarly, in Imbaba (H/W = 2), extensive and intensive green roofs contribute to air temperature reductions of up to 1.4 K and 1.6 K, respectively.

Moreover, extensive, and intensive green roofs have lower U-values (coefficient of heat transmission) than conventional roofs. The low U-values have a great impact on heat transfer and air temperature reduction. The increase in soil substrate depth of the green roof could lead to air temperature and buildings' energy reduction efficiently.

These results confirm that using green roofs in Cairo is a more important measure that could be achieved by the cooperation of the residents as the decisions can be taken faster than the governmental decision of allocating spaces for green areas. This study can support decision-makers in Cairo and similar environments. The intensive green roof does enhance PET in relation to building height. It reduces PET in 12m height buildings by 1.5 K. Another new finding from this study is that urban density and aspect ratio play an important role in the effect of green roofs on air temperature, buildings' energy, and PET reduction. The informal settlements, such as Imbaba, have extremely dense built-up areas, deep canyons, and a lack of outdoor spaces available for planting trees and grass.

Therefore, the strong effect of green roofs on air temperature reduction in these areas confirms green roofs as a suitable mitigation strategy that does not require open outdoor spaces.
These results confirm the efficiency of green roofs in high density areas in Cairo is greater than the trees and grass as there is not enough space to allocate them.

Green roofs will change the surface albedo which is one of the factors of creating UHI (Oke 1987) This effect can be reduced by increasing albedo (the reflection of incoming radiation away from a surface) or by increasing vegetation cover with sufficient soil moisture for evapotranspiration.

Green roofs are considered an innovative solution for the informal areas where the poor residents live. These roofs could be planted with productive plants that can help the people to earn money, enhance their income, and reduce their electricity bills. Besides, the extensive green roofs could be planted with other plants that are widely consumed, such as different types of vegetables and can be a productive project to support the residents financially.
Also, green roofs can play a great role in increasing socialization between the residents by creating shared semi-public spaces.
Green roofs can enhance the lives of the urban dwellers and can be a central element for the well-being of the inhabitants.
Green roofs can be useful in storm water retention by reducing the surface runoff which makes the city suffers every winter due to lack of storm water management.

Extensive green roofs have a lower biomass which have a little potential to offset carbon emissions from the city, on the other hand intensive roof gardens can support woody vegetation can make a significant contribution as an urban carbon sink and help with raising the air quality in the city is it can trap the airborne particulates such as Nitrogen oxide and dust.
Green roofs can play a role in increasing biodiversity or restoring it after being destroyed by excessive urbanization.
The ecosystem created by the green roof’s interacting components mimics several key properties of ground level vegetation that are not in the conventional roof, it will work as

any other constructed ecosystem, it can provide support to shallow soil habitats and their accompanying biodiversity.

6.1 SWOT analysis.

Table 16. Swot analysis.

Strength	**Weakness**
1. Environmental benefits: Green roofs help mitigate urban heat island effect, reduce air pollution, and improve air quality by absorbing carbon dioxide and producing oxygen. 2. Energy efficiency: They provide insulation, reducing the need for heating and cooling, thus lowering energy costs for buildings. 3. Stormwater management: Green roofs absorb and filter rainwater, reducing stormwater runoff and alleviating pressure on drainage systems. 4. Aesthetic appeal: They enhance the visual appeal of buildings and urban landscapes, contributing to biodiversity and creating green spaces in urban areas.	1. High initial costs: Installation and maintenance of green roofs can be expensive, deterring some building owners from adopting this technology. 2. Structural considerations: The weight of green roofs can pose structural challenges, requiring reinforcement of buildings to support the additional load. 3. Maintenance requirements: Regular maintenance, including watering, weeding, and pruning, is necessary to ensure the health and longevity of green roofs. 4. Limited applicability: Green roofs may not be suitable for all buildings or climates, depending on factors such as roof slope, building height, and regional climate conditions.
Opportunity	**Threats**
1. Government incentives: Increased awareness of environmental benefits may lead to government incentives, grants, or tax breaks to encourage the adoption of green roofs. 2. Urban development: As cities grow, there is a growing need for sustainable building solutions, presenting opportunities for the expansion of green roof installations. 3. it can introduce urban farming with crops production either for the residents use or the commercial use 4. can be an opportunity to Enhancing and retrieve the lost biodiversity in town 5. can be an opportunity to retain stormwater instead of losing it to the sewage	1. Economic factors: Economic downturns or budget constraints may limit investment in green roof projects by both private and public sectors. 2. Regulatory barriers: Stringent building codes, zoning regulations, or lack of supportive policies may hinder the widespread adoption of green roofs in some regions. 3. Competition: Other sustainable building solutions, such as solar panels or cool roofs, may compete with green roofs for market share. 4. Climate change: Extreme weather events, such as heavy rainfall or droughts, may impact the performance and viability of green roofs, affecting their adoption and effectiveness in the long term.

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