Tanta University
Faculty of Engineering
Architectural Department

Green Infrastructure as An Approach to Reduce the Urban Heat Island Effect in Existing Cities

A THESIS

Submitted in the partial fulfilment of the requirement for the Degree of Master of Science in Engineering (Architecture Engineering), Tanta University, Egypt

Prepared by

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2025

بِسْمِ اللهِ الرَّحْمَنِ الرَّحِيمِ

﴿ وَقُلْ رَبِّ زِدْنِي عِلْمًا ﴾

[طه :114]

Abstract

Rapid urbanization and overpopulation, along with a lack of green space, led to an increase in air temperature, lowering the rate of thermal comfort in dense urban areas, decreasing air quality, and increasing the urban heat island (UHI) phenomenon, particularly in existing cities. As a result, the research aims to reduce the UHI effect and improve the thermal performance of existing Egyptian cities by adopting green infrastructure (GI) principles and demonstrating their effectiveness on the UHI phenomenon. This research concentrates on the UHI phenomenon as one of the environmental issues facing urbanization and includes a review of green infrastructure (GI) as one of its mitigation strategies. In addition to analyzing different existing urban districts that used green infrastructure (GI) in their urban design to evaluate its effectiveness on urban thermal performance, The research also includes an applied study on Mahalla Al-Kubra city, Gharbia Governorate, Egypt, in which different green infrastructure (GI) scenarios are studied and analyzed using the environmental simulation program ENVI-met to identify their effect on thermal performance by analyzing the air temperature, mean radiant temperature (MRT), surface temperature and predicted mean vote (PMV), which affect the UHI phenomenon. The results show that adopting green infrastructure principles significantly impacts lowering air temperature, mean radiant temperature (MRT), and improving thermal comfort, confirming that green infrastructure is highly effective in reducing UHI.

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﴿رَبِّ أَوْزِعْنِي أَنْ أَشْكُرَ نِعْمَتَكَ الَّتِي أَنْعَمْتَ عَلَيَّ وَعَلَىٰ وَالِدَيَّ وَأَنْ أَعْمَلَ صَالِحًا تَرْضَاهُ
وَأَدْخِلْنِي بِرَحْمَتِكَ فِي عِبَادِكَ الصَّالِحِينَ﴾ النمل :19

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May this work serve as a valuable contribution to the field and inspire others to explore further. It reflects my sincere commitment to advancing knowledge and represents the collective support, guidance, and effort of everyone who has accompanied me on this journey. I hope this work not only broadens understanding but also provides a foundation for future research, fostering growth, innovation, and positive change. With humility, I offer it as a small yet dedicated step toward enriching our shared knowledge and serving those who follow in this path.

Abbreviations

BLUHI	Boundary Layer Urban Heat Island
CLUHI	Canopy Layer Urban Heat Island
EPA	Environmental Protection Agency
GHG	Greenhouse Gas
GI	Green Infrastructure
GIS	Geographic Information Systems
LID	Low-Impact Development
LST	Land Surface Temperature
LWS	Living Wall System
MRT	Mean Radiant Temperature
PMV	Predicted Mean Vote
SUHI	Surface Urban Heat Island
SVF	Sky View Factor
Tair	Air Temperature
Ts	Surface Temperature
UHI	Urban Heat Island
UGI	Urban Green Infrastructure
UV	Ultraviolet rays
WH	Water Harvesting
WHO	World Health Organization

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CHAPTER 1

INTRODUCTION

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1.1. Introduction

Today, cities face severe environmental challenges due to unplanned urbanization and overpopulation. The rapid growth of cities has led to a surge in energy demand and consumption, resulting in escalated levels of air pollution and greenhouse gas emissions. Cities consume over two-thirds of the world's energy and are responsible for over 60% of greenhouse gas emissions.[1]. One of the consequences of increased GHG emissions is the temperature rise, it has detrimental effects on ecosystems, causing disruptions in natural habitats and contributing to the acceleration of climate change. The European Commission predicts that the global urban population will nearly double from 55% in 2018 to 68% by 2050, largely because of rapid urbanization and industrialization.[2], inland cities may experience temperatures 3–5ºC higher than surrounding areas due to the so-called heat island effect of large concrete expanses and lack of green cover[3]. As a result, urban heat islands have emerged as a major issue in the twenty-first century.[4].

The urban heat island (UHI) effect is an example of local climate change, it refers to the phenomenon where urban areas experience higher temperatures compared to surrounding areas[5]. Hot weather can aggravate health conditions like cardiovascular and respiratory disease, as well as cause heat stroke and death[6]. When the core body temperature exceeds 40°C, the central nervous system malfunctions, causing delirium, convulsions, or coma[7]. As cities become more densely populated, future populations are more likely to suffer from urban overheating[8]. According to the United Nations-Habitat World Cities Report 2024, 2 billion urban residents will face significant temperature increases by 2040, with more than one-third of the city's mean annual temperatures exceeding 29°C. In green areas in our cities, demand for mitigating heat and promoting well-being decreased from 19.5% of urban land in 1990 to 13.9% in 2020, Climate-related

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[7] Tabassum, Raza, & Shah, 2019, *Outcome of heat stroke patients referred to a tertiary hospital in pakistan: A retrospective study*, p. 457

[8] Macintyre & Heaviside, 2019, *Potential benefits of cool roofs in reducing heat-related mortality during heatwaves in a European city*, p. 430

disasters, like floods, cyclones, and droughts, have increased[1]. Thousands of deaths are annually reported due to heat-related illnesses, around 50,000 people died in Europe during the heat wave of the summer of 2003[2]. In Victoria, a heatwave in January 2009 led to 374 deaths[3]. In addition, UHI increases urban pollution concentrations and has an impact on local meteorology by altering wind patterns, forming clouds and fog, increasing humidity, and changing precipitation rates[4]. Therefore, it is critical to develop solutions to mitigate urban heat islands.

The World Health Organization (WHO) highlighted heat events as one of the main challenges for urban planning and policy design.[5]. Urban planners play a crucial role in addressing the issue of urban overheating, preventing diseases in the 21st century, influencing air quality, space, water, food, and healthcare access, and fostering healthier environments and societies.[6]. In reflection, cities adapt mitigation strategies water water-sensitive urban design, cool and reflective materials, and green infrastructure implementation.

This research focuses on green infrastructure (GI) as a mitigation strategy. GI is an effective way to reduce heat accumulation in the urban environment because it shades hot surfaces, increases evapotranspiration cooling, and modifies wind patterns[7]. Green infrastructure refers to natural or semi-natural networks of green (vegetated) and blue (water-covered) spaces and corridors[8], GI is integrative, multi-functional and provides ecological and social benefits[9]. It promotes biodiversity creation, improves air, and water quality, provides recreational opportunities, reduces energy use, improves health, and stormwater capture, increases amenities, noise

[1] UN-Habitat, 2024, *World Cities Report 2024: Cities and Climate Action*

[2] Mirzaei & Haghighat, 2010, *Approaches to study Urban Heat Island - Abilities and limitations*, p. 2192

[3] Briony Norton et al., 2013, *Planning for a Cooler Future : Green Infrastructure to Reduce Urban Heat: Climate Adaptation for Decision-makers*, p. 6

[4] Mirzaei & Haghighat, 2010, *Approaches to study Urban Heat Island - Abilities and limitations*, p. 2192

[5] Ellena et al., 2023, *Micro-scale UHI risk assessment on the heat-health nexus within cities by looking at socio-economic factors and built environment characteristics: The Turin case study (Italy)*, p. 2

[6] UN-Habitat & World Health Organization, 2020, *Integrating health in urban and territorial planning: a sourcebook*, p. xi

[7] Briony Norton et al., 2013, *Planning for a Cooler Future : Green Infrastructure to Reduce Urban Heat: Climate Adaptation for Decision-makers*, p. 9

[8] Jones & Somper, 2014, *The role of green infrastructure in climate change adaptation in London*, p. 191

[9] Hansen, Rall, Rolf, & Pauleit, 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 3

attenuation, and pollution reduction[1]. Planners can incorporate green infrastructure, such as parks and trees, into city designs to reduce the urban heat island effect and create more comfortable living environments for urban residents.

1.2. Problem Statement

The rapid and unplanned urbanization and overpopulation problems faced by existing cities led to the global economic crisis and environmental issues like climate change risks, the spread of pollutants, and the lack of green spaces in cities led to a rise in air temperature, which led to a lower rate of thermal comfort in the streets and urban surroundings in the city than the neighbouring rural areas, with the accumulation of heat inside cities over the years, led to a rise in temperatures during night within the urban areas than in the neighbouring rural areas; resulted in the emergence of the so-called phenomenon of the urban heat island.

1.3. Hypothesis

The concept of green infrastructure is not a new one, but it has to be widely propagated among residents. Green infrastructure can be a resilient and sustainable way to redesign existing cities, effectively mitigate the effects of UHI and provide thermal comfort in urban spaces.

1.4. Aim of Research

The main aim of the study is to develop solutions using the green infrastructure approach as an effective and sustainable solution for mitigating the urban heat island (UHI) phenomenon in existing cities. This can be achieved through:

- **Enhancing Urban Thermal Comfort:** Develop strategies to improve thermal comfort levels in streets and urban areas, creating better living conditions for residents.
- **Mitigating UHI and Climate Change:** Reduce the intensity of UHI and its contribution to climate change by integrating natural cooling mechanisms into urban designs.

[1] Briony Norton et al., 2013, *Planning for a Cooler Future : Green Infrastructure to Reduce Urban Heat: Climate Adaptation for Decision-makers*, p. 10; Jones & Somper, 2014, *The role of green infrastructure in climate change adaptation in London*, p. 191

- **Promoting sustainable urban design:** Adopt green infrastructure principles to transform existing cities into healthier, more resilient, and more sustainable environments.

1.5. Methodology

- Theoretical approach:

Literature Review discusses urban heat island phenomenon (UHI), its two types; (Atmospheric and surface urban heat island), factors, causes and impact of UHI on the urban environment and human comfort. Review existing UHI mitigation strategies. A primary focus on green infrastructure (GI), discussing GI principles, elements, and functions. Identify its practices and examples of GI in urban areas for UHI mitigation.

- Analytical Approach:

Analyzing a group of urban neighbourhoods and districts that have implemented green infrastructure in their urban areas in hot dry climate regions, hence analyzing GI elements, principles, and their effect on the land surface temperature.

- Applied Approach:

Using ENVI-met software to simulate the impact of various GI scenarios in El-Mahalla El-Kubra, an Egyptian city, to determine the most effective GI strategy for reducing UHI in similar urban contexts.

1.6. Study Outline

The study consists of six chapters. Chapter 1 is a general introduction to the study, including an overview, problem statement, aims of research, hypothesis, objectives, and methodology.

Chapter 2 defines the problem of urban heat island (UHI), its types, factors that affect it, the causes of its intensity variation and the economic, environmental, social, and biological impact of UHI, as well as the mitigation strategies to reduce the harmful effects of UHI.

Chapter 3 defines the concept of green infrastructure (GI), its elements, the main principles for designing GI, the functions (environmental, biological, economic, and social functions) of GI, and also summarizes the GI practices.

Chapter 4 analyzes the impact of using various green infrastructure elements and principles in some existing urban districts in both local and international districts that have used green infrastructure (GI) in their urban design to assess its effectiveness on urban thermal performance in the same climatic zone.

Chapter 5 uses the ENVI-met simulation program to simulate multiple green infrastructure (GI) scenarios in the El-Mahalla El-Kubra city by adopting GI principles and demonstrating their effectiveness on the UHI phenomenon by analyzing air temperature, surface temperature, mean radiant temperature, and thermal comfort in city areas.

Chapter 6 is the study's conclusion and recommendations.

Fig. 1-1 illustrate research structure.

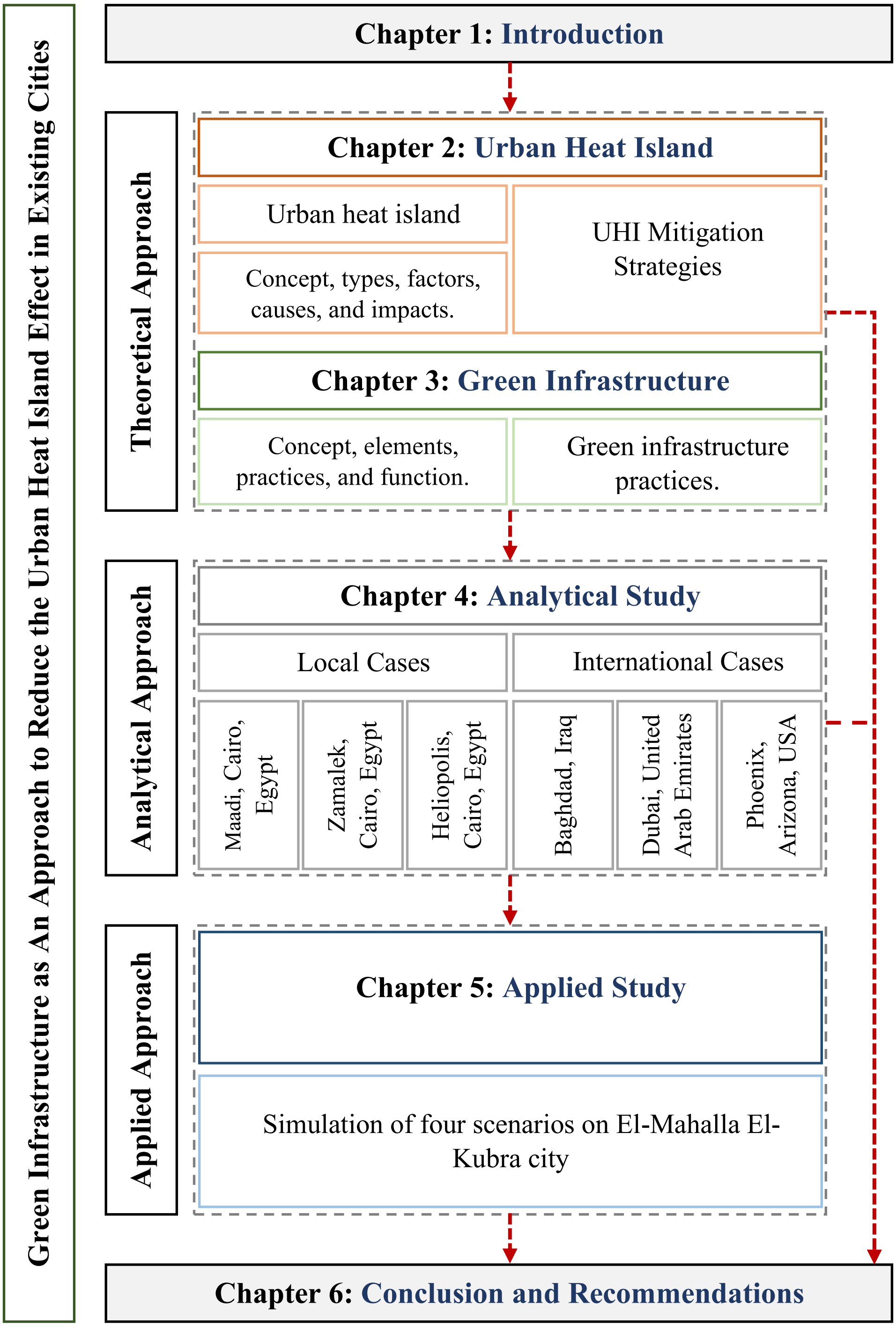

Fig. 1-1 Research Structure

CHAPTER 2

URBAN HEAT ISLAND

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2.1. Introduction

Urban Heat Island (UHI) is a global issue that threatens the habitability of cities and the urban environment. It is characterized by a significant increase in temperatures in cities compared with the areas that are directly surrounded.[1]. Hundreds of global experimental studies have documented the heat island phenomenon, which significantly impacts urban microclimate by reducing thermal comfort, increasing energy consumption during summer, increasing pollution, and expanding the city's ecological footprint, making it the most documented climate change phenomenon.[2]. This chapter explains urban heat islands (UHIs), their types, causes, and impacts on the environment, economy, social, and biological, and discusses mitigation strategies and their benefits.

2.2. Concept of Urban Heat Island (UHI)

The urban heat island (UHI) effect is widely acknowledged as a heat accumulation phenomenon caused by urban construction and human activity[3] (Fig. 2-1), UHI phenomena like "An Island" occur when hot surface air is concentrated in urban areas and gradually decreases in nearby temperatures in suburban/rural areas (Fig. 2-2). Based on an analysis of the incoming and outgoing energy flux from an urban surface system, the UHI phenomenon was explained as an "urban energy balance."[4]. The temperature difference is generally higher at night than during the day, and it is most noticeable when the winds are weak. UHI is more evident in the summer and winter. Modifying land surfaces is the main cause of the urban heat island effect. Secondary contributors include waste heat generated by energy consumption. As a population center grows, its area expands, and its average temperature rises. Heat islands are areas that are consistently hotter than the surrounding area, whether they are populated or not[5]. Daytime temperatures in cities increased by 1-3˚C, while nighttime by 12˚C[6]. The urban heat island effect is closely related to the properties and structure of the underlying surface, vegetation coverage, population

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[1] Mohajerani, 2018, *The Urban Heat Island Effect, its Causes, and Mitigation, with Reference to the Thermal Properties of Asphalt Concrete*, p. 3

[2] Santamouris et al., 2012, *Improving the microclimate in a dense urban area using experimental and theoretical techniques - The case of Marousi, Athens*, p. 1

[3] L. Yang, Qian, Song, & Zheng, 2016, *Research on Urban Heat-Island Effect*, p. 11

[4] Ningrum, 2018, *Urban Heat Island towards Urban Climate*, p. 1

[5] Kumar Samanta & Mahavidyalaya, n.d., *Urban Heat Island*, p. 1

[6] Bek, Azmy, & Elkafrawy, 2018, *The effect of unplanned growth of urban areas on heat island phenomena*, p. 3

density, and weather conditions. Meanwhile, as urbanization continues, the scale and intensity of the UHI effect will grow[1]. The term urban heat island usually refers to the relative warmth of air temperature near the ground (canopy layer)[2].

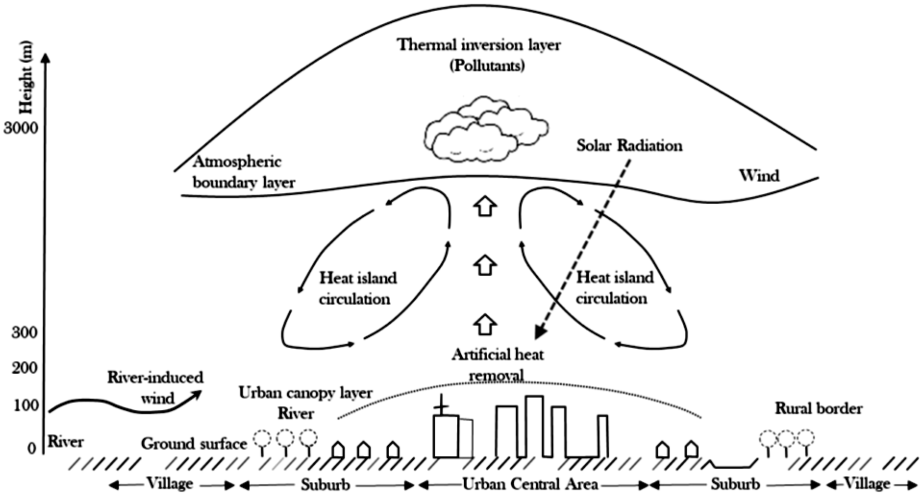

Fig. 2-1 Urban heat island (UHI) effect. (Source: Miller (2018), p. 14)

Fig. 2-2 The Urban Heat Island Effect Numerically. (Source: Hewitt V et al.(2014) p.8)

Fig. 2-3 shows two sections[3]:

Section A shows the contrast in cooling between urban and rural areas. Both surfaces begin to cool several hours before sunset, but rural areas cool rapidly compared to urban areas that retain heat better. Rural temperature during calm atmospheric conditions is also seen to fall lower than urban temperatures.

Section B shows the heat island intensity growing mid-late afternoon and at its highest a few hours after sunset.

[1] L. Yang et al., 2016, *Research on Urban Heat-Island Effect*, p. 12
[2] Voogt, 2008, *How Researchers Measure Urban Heat Islands*, p. 4
[3] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 5; Voogt, 2008, *How Researchers Measure Urban Heat Islands*, p. 4

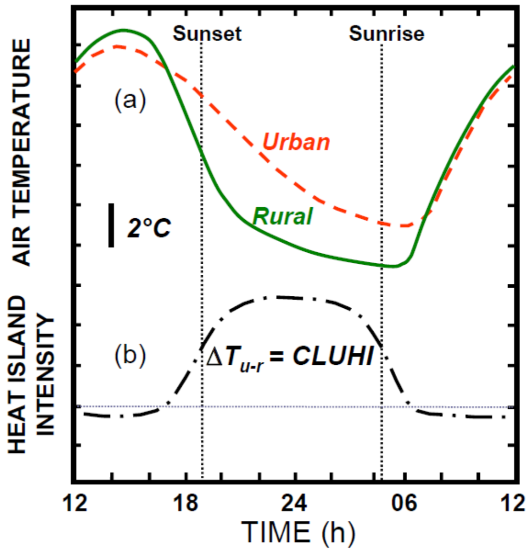

Fig. 2-3 Conceptual Drawing of the Diurnal Evolution of the Urban Heat Island during Calm and Clear Conditions (a) Air temperature (b) Heat Island intensity.(Source: Voogt (2008), p. 4)

2.3. Types of Urban Heat Islands

Two main types of heat islands differ in their formation, methods for identifying and measuring them, and impacts: Surface and atmospheric Urban Heat Island.[1]. Table 2-1 summarizes the basic characteristics of each type of heat island.

Table 2-1 Basic Characteristics of Surface and Atmospheric Urban Heat Island. (Source: Hashem Akbari et al (2008), p.3, Vujovic, Haddad, Karaky, Sebaibi, & Boutouil, (2021), p.461)

Feature	***Atmospheric UHI***	***Surface UHI***
Temporal Development	It may be small or non-existent during the day. most intense at night.	Present at all times of the day and night. most intense during the summer.
Peak Intensity (Most intense UHI conditions)	Less variation: - Day: -1 to 3°C - Night: 7 to 12°C	More spatial and temporal variation: - Day: 10 to 15°C - Night: 5 to 10°C
Typical Identification Method	Direct measurement: - Fixed weather stations - Mobile traverses	Indirect measurement: - Remote sensing
Typical Depiction	Isotherm map Temperature graph	Thermal image

[1] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 3; Vujovic, Haddad, Karaky, Sebaibi, & Boutouil, 2021, *Urban Heat Island: Causes, Consequences, and Mitigation Measures with Emphasis on Reflective and Permeable Pavements*, p. 461; Q. Yang, Huang, & Li, 2017, *Assessing the relationship between surface urban heat islands and landscape patterns across climatic zones in China*, p. 1

2.3.1. Atmospheric Urban Heat Island

The term "atmospheric urban heat island" refers to warmer air in urban areas compared to cooler air in nearby areas. It is often weak in the late morning and throughout the day, becoming more pronounced after sunset due to the slow release of heat from urban infrastructure. The timing of this peak, however, is determined by the properties of urban and rural surfaces, the season, and the prevailing weather conditions[1]. There are two different types:

a. Boundary Layer Urban Heat Island (BLUHI)

The BLUHI is the layer above the average height of the buildings (Fig. 2-4), as measured by weather towers, remote sensing, or aircraft[2].

BLUHI is completely influenced by weather at the mesoscale. It is formed by a plume oriented in the direction of the wind and influenced by it. The plume is also formed by the addition of heat from roofs and tops of urban street canyons, as well as heat from sources such as vents and chimneys, in other words, anthropogenic activity[3].

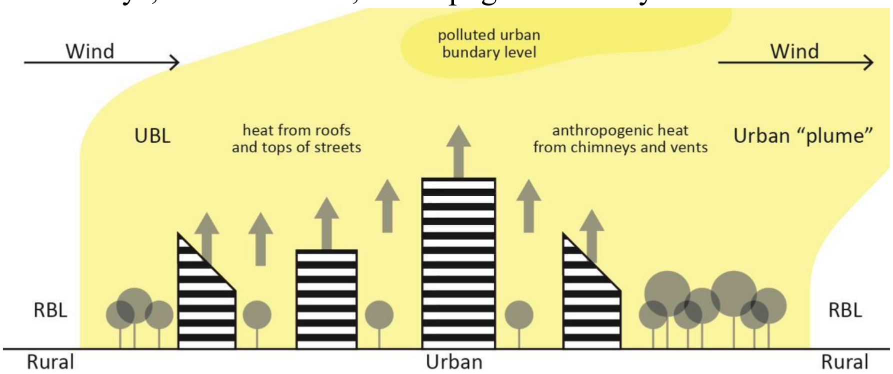

Fig. 2-4 Schematic Depiction of BLUHI. (Source: Branea A-M et al. (2016), p. 3.)

The most common method of measuring BLUHI is by temperature sensors mounted on the tallest buildings in both urban and rural regions. These sensors must be kept at 10 tower diameters for open towers and 3 structural diameters for solid towers from the towers themselves[4]. Tethered balloons and temperature profiles, but these are subject to aviation, storm, and wind restrictions. Only aviation regulations apply to free balloons. To accurately identify a UHI,

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[1] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 3

[2] Moyer, 2016, *Assessing The Urban Heat Island Of A Small Urban Area In Central Pennsylvania Along The Susquehanna River*, p. 6

[3] Branea et al., 2016, *Challanges regarding the study of urban heat islands. Ruleset for researchers*, p. 3

[4] Voogt, 2008, *How Researchers Measure Urban Heat Islands*, p. 10

radiosondes must take at least two measurements at the same time[1]. The traverse method is by traversing aircraft-mounted temperature sensors flown across an urban area, and the remote method[2]. Shown in Table 2-2.

Table 2-2 Types of BLUHI measurements and challenges for each. (Source: Branea A-M et al. (2016), p. 5.6)

UHI Types:	***Measurement Approach***		***Challenges***
Boundary layer urban heat island (BLUHI)	Fixed	Tower temperature sensors	Keeping a faraway distance from the tower
		Tethered balloons	Subject to restrictions of aviation, wind, and storm
		Radiosondes	Subject to restrictions of aviation
	Traverse	Traverse sensors	Possible overestimation due to uncertain trace and positioning
	Remote	SODAR – sound detection and ranging	Urban deployment problems
		Microwave radiometers	
		RASS – radio acoustic sound system	
		LiDAR - ceilometer	

b. Canopy Layer Urban Heat Island (CLUHI)

The CLUHI is a microscale to mesoscale atmospheric warming effect caused by cities, exists in the layer of air that extends just above the surface where people live, up to the average height of buildings, and below the tops of trees and roofs. They are formed underneath a line that contains, at most, the top of every building in the city, especially the tallest ones[3]. The CLUHI is particularly significant as it refers to the air temperature difference 2 meters above the ground, where most outdoor activities occur[4]. It is formed through the absorption of solar radiation by low-reflectance and insulated surfaces that lead to high daytime urban temperatures. There is also an addition of anthropogenic heat, humidity, and pollutants, but there is practically no decisive influence from the local winds and turbulence[5] (Fig. 2-5).

---

[1] Branea et al., 2016, *Challanges regarding the study of urban heat islands. Ruleset for researchers*, p. 3

[2] Ibid.p. 5,6

[3] Ibid.p. 3; Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 3; Moyer, 2016, *Assessing The Urban Heat Island Of A Small Urban Area In Central Pennsylvania Along The Susquehanna River*, p. 6

[4] Vujovic et al., 2021, *Urban Heat Island: Causes, Consequences, and Mitigation Measures with Emphasis on Reflective and Permeable Pavements*, p. 461

[5] Branea et al., 2016, *Challanges regarding the study of urban heat islands. Ruleset for researchers*, p. 3

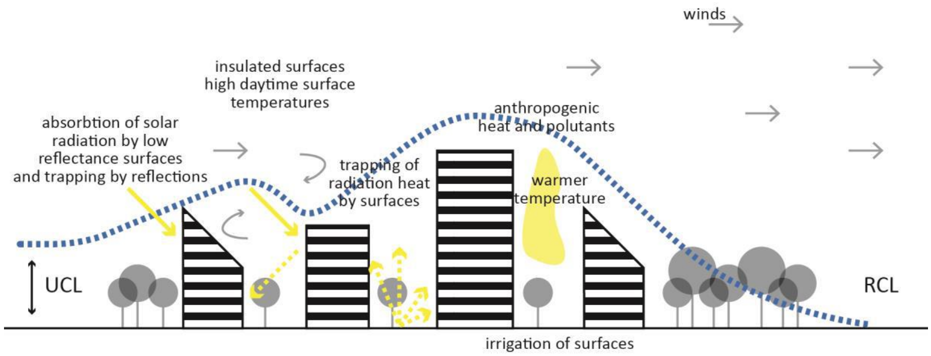

Fig. 2-5 Schematic depiction of CLUHI. (Source: Branea A-M et al. (2016), p. 5).

In fixed measurements, temperatures are typically measured between 1-2 meters above ground at two or more stationary sites or multiple sites traversed by vehicle across a city[1]. Table 2-3 shows the types of CLUTI measurement approaches and the challenges for each. To provide accurate measurements, the sensors must be well-shaded and ventilated, and their placement must address the following issues[2]:

1. the main objective of the measurement.
2. the sensor source location.
3. the variety of rural areas that surround the main city.

Traverse sensors are installed in vehicles with identical paths at the start and end points. Innovations for mobile systems with high-sensitivity temperature sensors are proposed to avoid exhaust influences and collect comparable vehicle speed observations. These sensors provide accurate data for monitoring conditions, and by using open-source platform prototypes, implementation costs can be reduced[3].

Table 2-3 Types of CLUHI measurements and challenges for each. (Source: Branea A-M et al. (2016), p. 4).

UHI Types:	***Measurement Approach***		***Challenges***
Canopy layer urban heat island (CLUHI)	Fixed	Standard – grass	Adequate environment conditions: shade and ventilation
		Non-standard – roof, roadside	
	Traverse	Automobile	Variation of vehicle speed. Instrument exposure High cost.

[1] Moyer, 2016, *Assessing The Urban Heat Island Of A Small Urban Area In Central Pennsylvania Along The Susquehanna River*, p. 6

[2] Branea et al., 2016, *Challanges regarding the study of urban heat islands. Ruleset for researchers*, p. 3

[3] Ibid.p. 4

In terms of CLUHI, the heat island reaches its peak at night in clear weather and may be small or even zero during the day. This reflects the actual magnitude of UHI, which is low during the day but increases at night[1].

2.3.2. Surface Urban Heat Island (SUHI)

The SUHI are actual surface temperatures measured by aircraft, satellite, or direct surface measurements[2]. Fig. 2-6 shows a schematic depiction of SUHI. The surface temperature is strictly related to the energy balance governed by its properties[3]:

- The influence and orientation of the sun, wind, and sky.
- The ability to radiate and reflect solar and infrared waves.
- The surface moisture and its ability to evaporate.
- The surface is relatively rough.
- The conduction and diffusion of heat.

On a hot summer day, the sun can raise the temperature of exposed urban surfaces to 27-50°C above the air temperature, while shaded surfaces remain close to air temperatures. Surface urban heat islands exist both during the day and at night, with an average temperature difference of 10-15°C between developed and rural areas; nighttime temperature differences are typically lower than daytime temperature differences of 5-10°C.

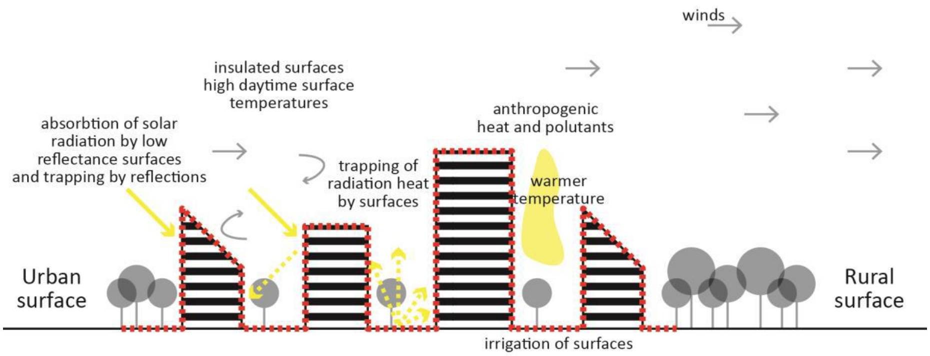

Fig. 2-6 Schematic depiction of SUHI. (Source: Branea A-M et al. (2016), p. 5)

Depending on the surface definition, the measurement of SUHI is remote in all the situations[4] (Table 2-4):

---

[1] Ibid.

[2] Moyer, 2016, *Assessing The Urban Heat Island Of A Small Urban Area In Central Pennsylvania Along The Susquehanna River*, p. 6

[3] Branea et al., 2016, *Challanges regarding the study of urban heat islands. Ruleset for researchers*, p. 4

[4] Ibid.p. 5,6

- The true 3D method estimates surface temperature using BIM software.
- Bird's eye 2D view has weather limitations and limited spatial coverage, while satellite imagery offers extensive coverage but is influenced by weather and atmosphere. The aircraft platform offers higher resolution and detail but has higher costs and irregular coverage.
- The ground-based method provides a good perspective of urban features and can avoid corrections due to atmospheric influence.

Table 2-4 Types of SUHI measurements and challenges for each. (Source: Branea A-M et al. (2016), p. 5,6)

UHI Types:	***Measurement Approach***		***Challenges***
Surface urban heat island (SUHI)	True 3D	Complete	Hard and software requests
	Bird's Eye 2D	Aircraft	Clear weather and resolution limitations. Irregular coverage. Limited accuracy. Data temporal resolution.
		Satellite: ATSR (Along Track Scanning Radiometer), Modis Data (Moderate Resolution Imaging, Spectroradiometer USA, Landsat USA, ASTER (Advanced Space-borne Thermal Emission and Reflection Radiometer) – Commercial USA, SEVIRI	
	Ground	Road	No major challenges

Urban heat island assessment often relies on thermal infrared satellite data, which may be inaccurate due to daytime capture and lack of correlation with air temperature, affecting UHI development[1].

2.4. Factors Affected UHI.

UHIs are created by a complex interaction of multiple factors. These mechanisms can contribute in varying amounts to UHI intensity in different urban areas, depending on the design, climate, and land use of the city[2]. Fig. 2-7 illustrates the factors affecting the UHI process[3].

[1] Ibid.p. 5
[2] Moyer, 2016, *Assessing The Urban Heat Island Of A Small Urban Area In Central Pennsylvania Along The Susquehanna River*, p. 6
[3] Voogt, 2008, *How Researchers Measure Urban Heat Islands*, p. 7; Vujovic et al., 2021, *Urban Heat Island: Causes, Consequences, and Mitigation Measures with Emphasis on Reflective and Permeable Pavements*, p. 462

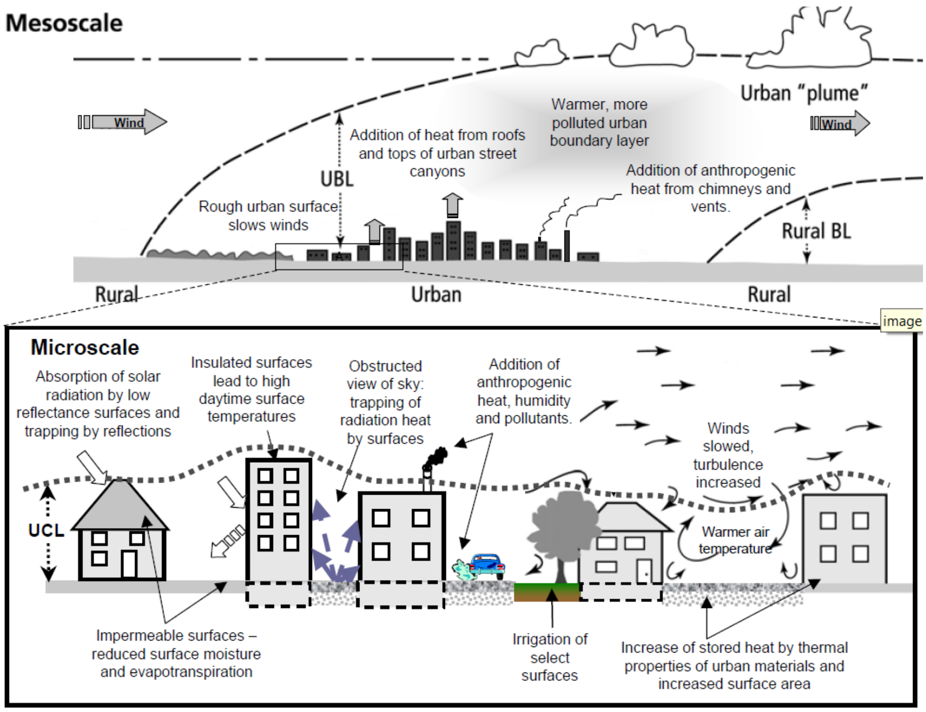

Fig. 2-7 Factors that affected the UHI process in mesoscale and microscale.(Source: Vujovic et al. (2021), p.462, Voogt (2008), p. 6)

2.4.1. Anthropogenic Heat

Anthropogenic heat is heat produced by human activities such as heating, cooling, appliances, transportation, and industrial processes (waste heat emissions from industry, air conditioning, motor vehicles, etc.). It varies by urban activity and infrastructure, with energy-intensive buildings and transportation producing more heat. It can contribute to heat island formation in dense urban areas during the winter and year-round, affecting rural areas and summer temperatures[1].

[1] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 12; Moyer, 2016, *Assessing The Urban Heat Island Of A Small Urban Area In Central Pennsylvania Along The Susquehanna River*, p. 7; Vujovic et al., 2021, *Urban Heat Island: Causes, Consequences, and Mitigation Measures with Emphasis on Reflective and Permeable Pavements*, p. 462,463

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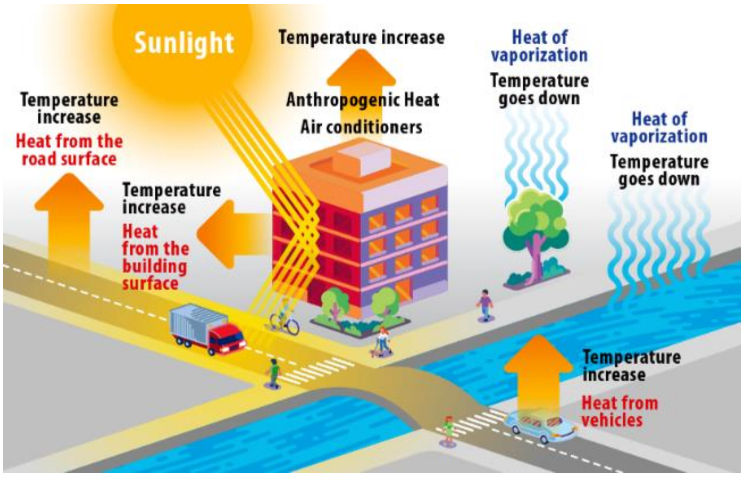

Fig. 2-8 Anthropogenic Heat Factors Contributing to Urban Heat Island Effect. (Source: https://www.pavetechinc.com/uhi-mitigation/ , Accessed: 23/11/2023)

2.4.2. Impervious Surfaces

Vegetation and open land in rural areas provide shade and reduce surface and air temperatures through evapotranspiration. Dry, impervious surfaces in urban areas cause vegetation loss and decreased water evaporation, resulting in elevated surface temperatures compared to air temperatures[1] (Fig. 2-9), The surface temperature of dark impervious surfaces in direct sunlight can reach up to 88˚C during the day, while moist vegetated surface with the same conditions can reach 18˚C[2].

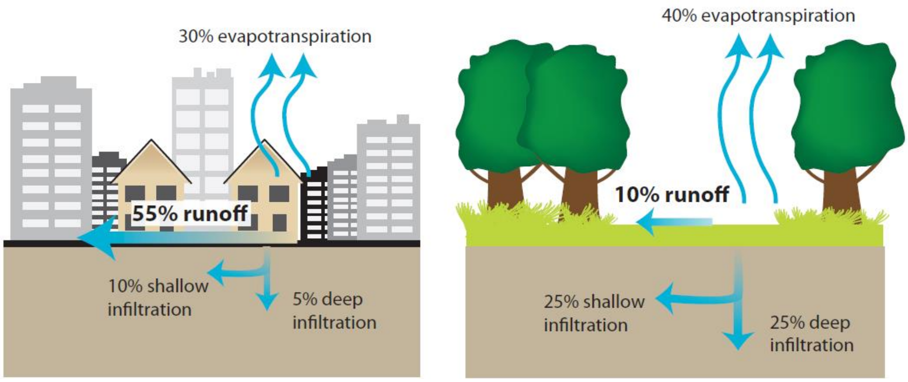

Fig. 2-9 Impervious Surfaces and Reduced Evapotranspiration. (Source: Hashem Akbari et al.(2008), p. 7).

[1] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 7; Moyer, 2016, *Assessing The Urban Heat Island Of A Small Urban Area In Central Pennsylvania Along The Susquehanna River*, p. 8

[2] Moyer, 2016, *Assessing The Urban Heat Island Of A Small Urban Area In Central Pennsylvania Along The Susquehanna River*, p. 8

2.4.3. Properties of Urban Materials

The properties of urban materials, including solar reflectance (Albedo), thermal emissivity, and heat capacity, influence heat island development by regulating sun energy reflection and absorption[1].

a. Solar Reflectance (Albedo):

Solar reflectance, also known as albedo, is the percentage of solar energy reflected by a surface. It is influenced by the color of the material, with darker surfaces having lower reflectance values. Roofs and paving in urban areas have lower albedo, resulting in less reflectivity and increased heat absorption, resulting in the formation of urban heat islands[2].

b. Thermal Emissivity

Thermal emittance is the ability of a surface to release absorbed heat[3]. Surfaces with a high emissivity stay cooler since they release heat more quickly. Except for metal, most building materials have high thermal emissivity values[4]. Natural surfaces have a higher albedo and a lower emissivity than urban surfaces[5].

c. Heat Capacity

Heat capacity is a material's ability to store heat. Building materials such as stone, concrete, asphalt, and steel have higher heat capacities than natural materials such as trees, grass, soil, and sand. Cities are more efficient at absorbing and storing solar energy as heat within their infrastructure, with downtown areas absorbing and storing twice as much heat during the day[6] .

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[1] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 8

[2] Ibid.p. 8,9; Moyer, 2016, *Assessing The Urban Heat Island Of A Small Urban Area In Central Pennsylvania Along The Susquehanna River*, p. 10

[3] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 9; Moyer, 2016, *Assessing The Urban Heat Island Of A Small Urban Area In Central Pennsylvania Along The Susquehanna River*, p. 10

[4] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 9

[5] Moyer, 2016, *Assessing The Urban Heat Island Of A Small Urban Area In Central Pennsylvania Along The Susquehanna River*, p. 10

[6] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 9; Moyer, 2016, *Assessing The Urban Heat Island Of A Small Urban Area In Central Pennsylvania Along The Susquehanna River*, p. 9,10

2.4.4. Population and Urban Density

Increases in urban density are typically associated with changes in surface properties as green space is reduced and built-up areas increase[1].

2.4.5. Urban Geometry

Urban geometry is the dimensions and spacing of buildings within a city[2]. Wind flow and the amount of radiation received and emitted by urban infrastructure are influenced by building height and spacing[3].

Urban canyons, characterized by narrow streets lined by tall buildings and dense buildings shaped like natural canyons, have competing effects on urban geometry. Tall buildings provide shade during the day, lowering surface and air temperatures. When sunlight reaches the canyon, however, the building walls absorb it, lowering the city's albedo and raising temperatures. At night, urban canyons obstruct cooling by preventing the transfer of heat from the infrastructure[4]. Cities with taller buildings close together will have higher UHI intensities than cities with smaller buildings spread out[5].

The "sky view factor" (SVF) is frequently used to describe the effects of urban geometry on urban heat islands[6]. SVF is a measurement of the percentage of sky visible from a given urban location concerning the percentage of buildings that obstruct it. The lower the percentage of SVF, the more long-wave radiation from the urban surface will be captured and cause warming within the city. However, high SVF urban geometry can result in lower daytime UHI since buildings shade surfaces from incoming solar radiation[7].

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[1] Vujovic et al., 2021, *Urban Heat Island: Causes, Consequences, and Mitigation Measures with Emphasis on Reflective and Permeable Pavements*, p. 463; Zhou et al., 2019, *Satellite remote sensing of surface urban heat islands: Progress, challenges, and perspectives*, p. 19

[2] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 10

[3] Bek et al., 2018, *The effect of unplanned growth of urban areas on heat island phenomena*, p. 3; Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 10; Moyer, 2016, *Assessing The Urban Heat Island Of A Small Urban Area In Central Pennsylvania Along The Susquehanna River*, p. 9

[4] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 10

[5] Moyer, 2016, *Assessing The Urban Heat Island Of A Small Urban Area In Central Pennsylvania Along The Susquehanna River*, p. 9

[6] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 12; Kim & Brown, 2021, *Urban heat island (UHI) variations within a city boundary: A systematic literature review*, p. 12

[7] Moyer, 2016, *Assessing The Urban Heat Island Of A Small Urban Area In Central Pennsylvania Along The Susquehanna River*, p. 9

2.4.6. Pollutants

Pollution exhaustion reduces air transparency, trapping heat in urban areas and preventing cooling through nighttime re-radiation, thus increasing the heat of urbanization[1].

2.4.7. Weather Conditions

The intensity of a UHI can be influenced by cloud cover and wind conditions. With low wind speeds, clear skies maximize solar energy reaching urban surfaces, allowing air to stagnate and warm due to reduced turbulence, whereas strong winds and cloud cover suppress heat islands[2].

2.4.8. Geographic Location

The formation of UHI is influenced by climate and topography, which are influenced by a city's geographic location. Water bodies can moderate temperatures and generate winds, whereas mountain ranges can either block or create wind patterns. When larger-scale effects, such as prevailing wind patterns, are weak, local terrain has a greater impact on heat island formation[3].

2.5. Causes of Variation in UHI Intensity

UHI have various intensities in different locations across the world due to many factors[4].

2.5.1. Diurnal Changes

UHIs are stronger at night than through the day since urban areas release daytime heat, causing less cooling in rural areas. The maximum UHI intensity occurs 3-5 hours after sunset (Fig. 2-3), whereas urban areas warm slowly after sunrise, potentially reaching a negative intensity several hours later. If rural areas warm quickly enough, they may overtake urban temperatures, resulting in an urban cool island (UCI), in which urban temperatures are lower than rural temperatures[5].

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[1] Bek et al., 2018, *The effect of unplanned growth of urban areas on heat island phenomena*, p. 3

[2] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 13; Moyer, 2016, *Assessing The Urban Heat Island Of A Small Urban Area In Central Pennsylvania Along The Susquehanna River*, p. 10,11

[3] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 13

[4] Moyer, 2016, *Assessing The Urban Heat Island Of A Small Urban Area In Central Pennsylvania Along The Susquehanna River*, p. 11

[5] Ibid.p. 11,12

2.5.2. Urban City Size

The intensity of UHI varies with urban area size, with studies showing strong UHIs in even the smallest cities[1]. Cities with a higher population density and aerodynamically different shapes are warmer due to increased activity. Large, tall buildings in cities act as obstacles, reducing wind speeds and increasing the UHI effect[2].

2.5.3. Urban City Form

The orientation, layout, and dimension of buildings in a city influence the exposure of urban surfaces to solar radiation. In turn, has an impact on shadow patterns, heat exchange, and airflow in urban areas[3], which has a significant impact on heat-trapping or dissipation[4].

2.5.4. Lack of Green Spaces

Tree planting and vegetation cover lower air temperature, Population growth and unplanned areas with less vegetation cover, increasing temperatures in densely populated urban areas[5].

2.5.5. River Effects

Large water bodies, such as oceans and lakes, can influence land temperatures by changing thermal circulation and causing land and sea breezes. Evaporation from water surfaces lowers surrounding temperatures as well. A study of Lake Superior discovered that near the shore temperatures are 1-2°C cooler in the spring, and summer, and 1°C warmer in the winter. Cities with open streets, wider rivers, and lower building density benefit more frequently from water body cooling. Closed-off areas, such as connected buildings or homes, block breezes, reducing overall cooling[6].

2.5.6. Intra-urban Variability

Long-term UHI studies frequently focus on a few meteorological stations, resulting in a limited understanding of city variability. According to a Rotterdam study, maximum UHI intensity has a significant positive relationship with building surface and impervious surface fractions, but a negative relationship with green surface

[1] Ibid.p. 13
[2] Rupard, 2019, *Urban Heat Islands: Causes, Impacts, & Mitigation*, p. 10
[3] Ibid.
[4] Climate Central, 2021, *Hot Zones: Urban Heat Islands*, p. 5
[5] Bek et al., 2018, *The effect of unplanned growth of urban areas on heat island phenomena*, p. 3
[6] Moyer, 2016, *Assessing The Urban Heat Island Of A Small Urban Area In Central Pennsylvania Along The Susquehanna River*, p. 14,15

fraction. Understanding intra-urban variability is critical for comprehending cities as heterogeneous mixtures of built and open spaces[1].

2.6. Impact of Urban Heat Island:

The UHI significantly impacts urban livability and environmental problems, affecting health, well-being, human comfort, and the local atmosphere[2]. While some heat island impacts are positive, such as extending the growing season for plants, the majority are negative and include[3]:

2.6.1. Economic Impact:

Urban heat islands have a negative impact on city functioning, livability, and health, and their frequency and intensity are increasing due to climate change. Factors such as demographics, economic development, and urban form all contribute to the city's and community's direct and indirect costs[4].

Global Economic Downturn: One of the most significant effects of UHI is the money spent on increased energy use, building and infrastructure maintenance, storm-water run-off management, and waste disposal[5].

2.6.2. Environmental Impact

UHIs have a local climate impact, increasing summer energy demand while also increasing air pollutants and greenhouse gas emissions. They also degrade water quality since warm water flows into local streams, stressing native species adapted to cooler aquatic environments[6].

a. Energy Consumption:

Ambient temperature increases cooling energy consumption, peak demand, and power generation capacity, requiring additional power

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[1] Ibid.p. 15

[2] Mohajerani, 2018, *The Urban Heat Island Effect, its Causes, and Mitigation, with Reference to the Thermal Properties of Asphalt Concrete*, p. 8

[3] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 13

[4] Lucas van Raalte, Michael Nolan, Praveen Thakur, Simon Xue, & Nicki Parker, 2012, *Economic Assessment of the Urban Heat Island Effect*, p. 1

[5] Vardoulakis, Karamanis, & Mihalakakou, 2014, *Heat island phenomenon and cool roofs mitigation strategies in a small city of elevated temperatures*, p. 4536

[6] Filho, Icaza, Emanche, & Al-Amin, 2017, *An evidence-based review of impacts, strategies and tools to mitigate urban heat islands*, p. 2

plants[1]. For every 0.6°C increase in summertime temperature, peak urban electric demand rises by 1.5-2%. Over the last few decades, 5-10% of total community electricity demand has been used to compensate for the heat island effect. Extreme heat events, exacerbated by urban heat islands, can overload systems, necessitating a utility to implement controlled, rolling brownouts or blackouts to avoid power outages[2].

b. Global Warming:

As the electric load increases, especially during peak hours, power plants produce more electricity and release more GHGs into the air, particularly CO2, contributing to global warming[3]. Elevated air temperatures contribute to the creation of ground-level ozone because of nitrogen oxides and volatile organic compounds reacting in sunlight[4]. As well as electricity that is generated using fossil fuels, which emit pollutants such as sulfur dioxide (SO2), nitrogen oxides (NOx), particulate matter (PM), carbon monoxide (CO2), and mercury (Hg)[5].

c. Air Quality:

Urban overheating increases energy demand, leading to increased air pollution and greenhouse gas emissions, affecting turbulent exchange and airflow in cities[6]. These pollutants are harmful to human health and contribute to air quality problems like acid rain[7].

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[1] Santamouris, 2020, *Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change*, p. 3

[2] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 13

[3] Hewitt, Mackres, & Shickman, 2014, *Cool Policies for Cool Cities: Best Practices for Mitigating Urban Heat Islands in North American Cities*, p. 9

[4] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 14; Santamouris, 2020, *Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change*, p. 8

[5] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 14; Vujovic et al., 2021, *Urban Heat Island: Causes, Consequences, and Mitigation Measures with Emphasis on Reflective and Permeable Pavements*, p. 467

[6] Santamouris, 2020, *Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change*, p. 8

[7] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 14; "Heat Island Impacts," n.d.

d. Water Quality:

Surface urban heat islands significantly decrease water quality, due to thermal pollution[1]. Heat is transferred to stormwater through pavement and rooftop surfaces that reach temperatures 27 to 50°C higher than air temperatures[2].

e. Climate Change

Cities indirectly contribute to climate change through their massive energy and material consumption, waste, and pollution production[3]. All previous points contributed directly to climate change as shown in Fig. 2-10

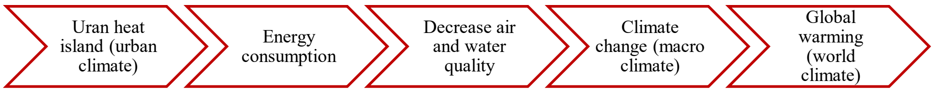

Fig. 2-10 UHI Environmental Impacts. (Source: Author)

2.6.3. Social and Humanitarian Impact

UHI has far-reaching consequences for people that go beyond mild thermal discomfort. including a deterioration of the living environment, an increase in energy consumption, an increase in ground-level ozone concentrations, and even an increase in mortality rates[4].

a. Human Health and Comfort

High temperatures in urban areas, reduced nighttime cooling, and air pollution all contribute to health problems including discomfort, respiratory difficulties, heat cramps, exhaustion, heat stroke, and heat-related mortality[5]. Indeed, heat is the deadliest natural disaster, causing more casualties than hurricanes, floods, and tornadoes combined[6].

b. Reduced Quality of Life

Excessive urban heat has a negative impact on residents' ability to enjoy outdoor amenities, exercise, and interact. Health problems are also more likely, and customers of energy utilities may face higher

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[1] "Heat Island Impacts," n.d.

[2] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 15; Vujovic et al., 2021, *Urban Heat Island: Causes, Consequences, and Mitigation Measures with Emphasis on Reflective and Permeable Pavements*, p. 468

[3] Vardoulakis et al., 2014, *Heat island phenomenon and cool roofs mitigation strategies in a small city of elevated temperatures*, p. 4536

[4] Ibid.

[5] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 14

[6] Hewitt et al., 2014, *Cool Policies for Cool Cities: Best Practices for Mitigating Urban Heat Islands in North American Cities*, p. 9

bills. Priorities in cities compete for limited resources, making cities less pleasant[1].

c. Poverty

Low-income neighbourhoods are disproportionately affected. People living in low-income households have less green space than those living in households earning more than twice the poverty line[2].

d. Anti-Social Behaviour

High temperatures have been linked to crime rates, as they can cause heat stress, discomfort, and increased aggression, resulting in societal harm and law violations[3].

2.6.4. Biological Impact

Water temperature has an impact on every aspect of aquatic life, particularly the metabolism and reproduction of many aquatic species. Warm stormwater runoff can cause rapid temperature changes in aquatic ecosystems, which can be particularly stressful. for example, Thermal stress and shock occur in brook trout when the water temperature changes by more than 1-2 degrees Celsius in 24 hours[4].

2.7. UHI Mitigation Strategies

Urban climatologists have studied heat islands for decades, but recent community concern has led to the development of heat island mitigation strategies including installing cool or vegetated green roofs, planting trees and vegetation, water bodies and replacing traditional paving surfaces with cool pavements[5].

2.7.1. Green Coverage

Trees and vegetation such as shrubs, vines, grasses, and ground cover (Fig. 2-11) help cool surface air temperatures through shading and evapotranspiration[6], which makes vegetation a simple and effective choice for reducing urban heat islands[7].

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[1] Ibid.

[2] Climate Central, 2021, *Hot Zones: Urban Heat Islands*, p. 7

[3] Lucas van Raalte et al., 2012, *Economic Assessment of the Urban Heat Island Effect*, p. 19

[4] Hashem Akbari et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Urban Heat Island Basics*, p. 15

[5] Vujovic et al., 2021, *Urban Heat Island: Causes, Consequences, and Mitigation Measures with Emphasis on Reflective and Permeable Pavements*, p. 468

[6] Razzaghmanesh et al., 2021, *Air Temperature Reductions at the Base of Tree Canopies*, p. 2; Rupard, 2019, *Urban Heat Islands: Causes, Impacts, & Mitigation*, p. 14

[7] Rupard, 2019, *Urban Heat Islands: Causes, Impacts, & Mitigation*, p. 14

Fig. 2-11 Parco Nord Milano is a regional park within Milan's metropolitan green belt.
(Source: Hansen R et al. (2017), p. 7.)

Shading: Tree shading reduces solar radiation below the canopy, lowering surface temperatures below the canopy, mitigating UHI by limiting solar energy storage, reducing heat energy direct gain, and providing outdoor thermal comfort[1]. Trees can be planted next to buildings to shade them, reducing the cooling demand for air conditioning by 25-80%[2], Maximum surface temperature reductions of 11 to 25°C for walls and roofs at two buildings have been observed, with vines reducing wall temperatures up to 20°C and tree shading reducing temperatures inside parked cars by about 25°C[3].

Evapotranspiration: Evapotranspiration is a process where water is evaporated from soil and trees, intercepting rainfall on leaves and converting liquid to gas, thereby cooling the air by using heat from the air[4].

- **Benefits of Vegetation and Green Spaces:**

It is more effective in outdoor urban areas, in addition to environmental functions, biological and vital functions economic functions, social and humanitarian functions.

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[1] Aboulnaga, Trombadore, Mostafa, & Abouaiana, 2024, *Livable cities - Urban Heat Islands Mitigation for Climate Change Adaptation Through Urban Greening*, p. 379

[2] Ibid.p. 381

[3] Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies: Trees and Vegetation*, p. 2,3

[4] Aboulnaga et al., 2024, *Livable cities - Urban Heat Islands Mitigation for Climate Change Adaptation Through Urban Greening*, p. 379; Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies: Trees and Vegetation*, p. 3

a. Environmental and natural functions:

- **Reduced Energy Use[1]:**

  Direct shading from trees and vegetation reduces the amount of energy required to cool buildings. differ depending on the:
  - Planting orientation and size
  - Planting distance from a building.

  Large trees planted near the west side of a building will provide more cooling energy savings than other plants.

- **Reduced Air Pollution and Greenhouse Gas Emissions:**

  Trees and vegetation improve air quality and reduce greenhouse gas emissions as following:

- Leaves remove pollutants from the air by filtering dust and absorbing pollutants through leaf stomata, react with water to form acids and chemicals, and intercept particulate matter from wind currents, reducing urban environmental pollutants like particulate matter (PM), nitrogen oxides (NOX), sulfur dioxide (SO2), carbon monoxide (CO), and ground-level ozone (O3)[2].
- Shade trees reduce evaporative emissions from parked vehicles as shade keeps parked cars cool by reducing evaporative emissions of volatile organic compounds (VOCs), a precursor pollutant in the formation of ground-level ozone[3].
- Plants and trees absorb and store carbon: trees store carbon by removing it from the atmosphere and sequestering it[4]. Carbon is released into the atmosphere or transferred to soil when they die or deposit litter, resulting in significant carbon storage in trees, vegetation, and soils[5].
- Plants and trees reduce power plant greenhouse gas emissions by reducing energy consumption:

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[1] Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies: Trees and Vegetation*, p. 5

[2] Aboulnaga et al., 2024, *Livable cities - Urban Heat Islands Mitigation for Climate Change Adaptation Through Urban Greening*, p. 378; Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies: Trees and Vegetation*, p. 6

[3] Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies: Trees and Vegetation*, p. 6,7

[4] Nowak, Greenfield, Hoehn, & Lapoint, 2013, *Carbon storage and sequestration by trees in urban and community areas of the United States*, p. 1

[5] Norman & Kreye, 2023, *How Forests Store Carbon*; Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies: Trees and Vegetation*, p. 7

Trees and vegetation have the potential to reduce energy demand[1]. Reduced energy consumption reduces the use of fossil fuels in power plants and thus reduces carbon emissions[2].

- **Enhanced Stormwater Management and Water Quality:** Urban forests, vegetation, and soils can mitigate stormwater runoff and water resource impacts by intercepting rainfall, absorbing water, and promoting plant-based water use[3].

b. Biological and vital functions

- **Improves Habitat:** Planting trees improves wildlife habitat, particularly when native plant species are used[4]. In urban areas, trees and vegetation provide numerous quality-of-life benefits by providing habitat for birds, insects, and other living organisms[5].

c. Economic functions

- **Reduced Pavement Maintenance Costs:** Tree shade can reduce pavement deterioration by 15-60% on residential streets, depending on the type of shade trees used[6].

d. Social and humanitarian functions

- **Improved Human Health:**
- Trees and vegetation reduce air pollution, reducing the negative health effects of poor air quality[7].
- Trees and vegetation reduce ultraviolet (UV) ray exposure, promoting health benefits such as less skin and eye damage and reducing negative environmental effects[8]. Skin cancer has been linked to prolonged UV exposure[9]. Dense tree canopies provide shade and reduce UV exposure.

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[1] Dettenmaier, Kuhns, Unger, & McAvoy, 2017, *Trees and Climate Change*, p. 6

[2] Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies: Trees and Vegetation*, p. 7

[3] Cotrone, 2022, *How Do Trees Reduce Stormwater and Flooding?*; Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies: Trees and Vegetation*, p. 8

[4] Aboulnaga et al., 2024, *Livable cities - Urban Heat Islands Mitigation for Climate Change Adaptation Through Urban Greening*, p. 378; U.S. EPA, 2010, *The Value of Green Infrastructure: A Guide to Recognizing Its Economic, Environmental and Social Benefits.*, p. 6

[5] Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies: Trees and Vegetation*, p. 8

[6] Ibid.

[7] Aboulnaga et al., 2024, *Livable cities - Urban Heat Islands Mitigation for Climate Change Adaptation Through Urban Greening*, p. 378; Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies: Trees and Vegetation*, p. 7,8

[8] Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies: Trees and Vegetation*, p. 7,8

[9] Rosen, 2024, *9 Things to Know About Sun Safety and Skin Cancer*

- Shade trees reduce heat gain in buildings, lowering indoor temperatures and reducing the health consequences of summer heat waves[1].
- **Noise Reduction:**
  Well-placed trees and shrubs can reduce urban noise[2]. Trees act as physical barriers to protect pedestrians in high-traffic areas, as the presence of trees frequently indicates the presence of pedestrians, trees near roads help to suppress the notion of a transportation corridor designed solely for vehicles and can help to calm traffic[3].
- **Enhanced Quality of Life:**
  Urban trees and vegetation have been linked to lower crime rates[4], higher property values, and psychological and social benefits such as reduced stress and aggressive behaviour[5].

2.7.2. Green Roofs

Green roofs are human-made structures installed on the roof of a building, are partially or entirely covered with vegetation and a growth medium (substrate), which serves both as a functional roof and a habitat for vegetation planted over a waterproofing membrane[6]. It can help communities mitigate urban heat islands, as it provides shade and removes heat through evapotranspiration[7]:

- Shading: Green roofs, including trees and vines, reduce sunlight transmission by shielding underlying layers from wind and UV radiation, reducing surface temperatures beneath plants.
- Evapotranspiration: it cools the air by evaporating water using heat from the air. Temperatures on green roofs vary depending on factors including composition, moisture content, location, and solar exposure.

[1] Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies: Trees and Vegetation*, p. 7,8
[2] Poletti-Harp, n.d., *New Research Proves Just How "Green" Urban Forests Are*; Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies: Trees and Vegetation*, p. 9
[3] Burden, 2006, *22 Benefits of Urban Street Trees*, p. 3
[4] McDowell, 2023, *The surprising way that millions of new trees could transform America*
[5] Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies: Trees and Vegetation*, p. 9
[6] Beaudoin, 2024, *Elevating Urban Landscapes: How Green Roofs Enhance Biodiversity and Address Climate Change in California*, p. 2; Temizel, Yazici, & Gülgün, 2021, *Planning, Design And Management In Landscape Architecture*; U.S. EPA, 2010, *The Value of Green Infrastructure: A Guide to Recognizing Its Economic, Environmental and Social Benefits.*
[7] Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies - Green roofs*, p. 1

A vegetated rooftop surface can be cooler than the surrounding air, whereas conventional rooftop surfaces can exceed ambient air temperatures by up to 50°C[1]. Green roofs can be installed on a variety of buildings, including industrial, educational, and government buildings, as well as offices, commercial properties, and residences[2].

a. Green Roof Types:

Green roofs are separated into several categories based on the depth of their growing media[3]. When a green roof is a simple 5 cm layer of hardy, alpine-like groundcover, it is called an "extensive" system; when it is a complex, fully accessible park with trees, it is called an "intensive" system[4]:

- **Extensive Green Roofs:**

  Extensive green roof systems (Fig. 2-12) are designed lightweight, cost-effective, and require minimal maintenance. They are ideal for extreme climates and require no permanent irrigation[5].

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[1] Ogaili & Sailor, 2015, *Measuring the Effect of Vegetated Roofs on the Performance of Photovoltaic Panels in a Combined System*, p. 8

[2] Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies - Green roofs*, p. 1

[3] U.S. EPA, 2010, *The Value of Green Infrastructure: A Guide to Recognizing Its Economic, Environmental and Social Benefits.*, p. 4

[4] Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies - Green roofs*, p. 4

[5] Baniya et al., 2018, *A Review of Green Roofs to Mitigate Urban Heat Island and Kathmandu Valley in Nepal*, p. 146; Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies - Green roofs*, p. 4

Fig. 2-12 'Historial de la Vendée' in France: An Example of an Extensive Green Roof.
(Source: Aboulnaga et al., (2024), p. 399)

- **Intensive Green Roofs:**

An intensive green roof (Fig. 2-13) provides a garden-like environment for building owners or managers, saving energy and providing a pleasant environment for occupants or the public. It requires more initial investment, long-term maintenance, and structural support to accommodate additional growing mediums and public use[1].

[1] Aboulnaga et al., 2024, *Livable cities - Urban Heat Islands Mitigation for Climate Change Adaptation Through Urban Greening*, p. 397,398; Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies - Green roofs*, p. 4

Fig. 2-13 Intensive Green Roof in Frankfurt, Germany. (Source: Ryan Bell 2008, p. 2)

b. Benefits of Green Roofs:

Green roofs provide similar benefits to trees and ground-level vegetation; however, green roofs have the advantage of being suitable for dense, built-up areas lacking ground-level planting space[1].

b.a. Environmental and natural functions

- **Reduced Energy Use:**

  Green roofs absorb and store heat when wet, acting as an insulator when dry, reducing energy consumption by reducing heating needs in winter and cooling energy demand in summer. However, their insulating properties vary due to their dynamic nature, especially in water storage, so they should not be used as a replacement for insulation[2]. Intensive roofs save more energy in Arid climates, while extensive roofs save more energy than conventional ones, and the savings increase with roof soil thickness[3].

[1] Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies - Green roofs*, p. 5
[2] Ibid.p. 6
[3] Beaudoin, 2024, *Elevating Urban Landscapes: How Green Roofs Enhance Biodiversity and Address Climate Change in California*, p. 24,25; Dasuni, Ramachandra, & Zainudeen, 2022, *Green roof as a technology towards sustainability: a perspective of benefits offered.*, p. 522

- **Reduced Air Pollution and Greenhouse Gas Emissions:**
  As well as vegetation, green roofs remove air pollutants and greenhouse gas emissions through dry deposition and carbon sequestration and storage. Green roofs help slow the formation of ground-level ozone by lowering air temperatures[1]. The type of vegetation on a green roof can affect its ability to reduce air pollution[2].

- **Enhanced Stormwater Management and Water Quality:**
  Green roofs absorb water from plants and vegetation, reducing urban stormwater runoff. The amount of rainfall retained is affected by the depth of the growing medium and the slope of the roof. Extensive roofs capture 50-100% of incoming rain, whereas intensive green roofs with thicker layers capture a higher percentage. While they cannot retain all the water, they can detain runoff for later release, reducing the runoff rate[3](Fig. 2-14).

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[1] Beaudoin, 2024, *Elevating Urban Landscapes: How Green Roofs Enhance Biodiversity and Address Climate Change in California*, p. 18; Ogaili & Sailor, 2015, *Measuring the Effect of Vegetated Roofs on the Performance of Photovoltaic Panels in a Combined System*, p. 9; Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies - Green roofs*, p. 7

[2] Dasuni et al., 2022, *Green roof as a technology towards sustainability: a perspective of benefits offered.*, p. 523

[3] Beaudoin, 2024, *Elevating Urban Landscapes: How Green Roofs Enhance Biodiversity and Address Climate Change in California*, p. 11; Ogaili & Sailor, 2015, *Measuring the Effect of Vegetated Roofs on the Performance of Photovoltaic Panels in a Combined System*, p. 10; Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies - Green roofs*, p. 8

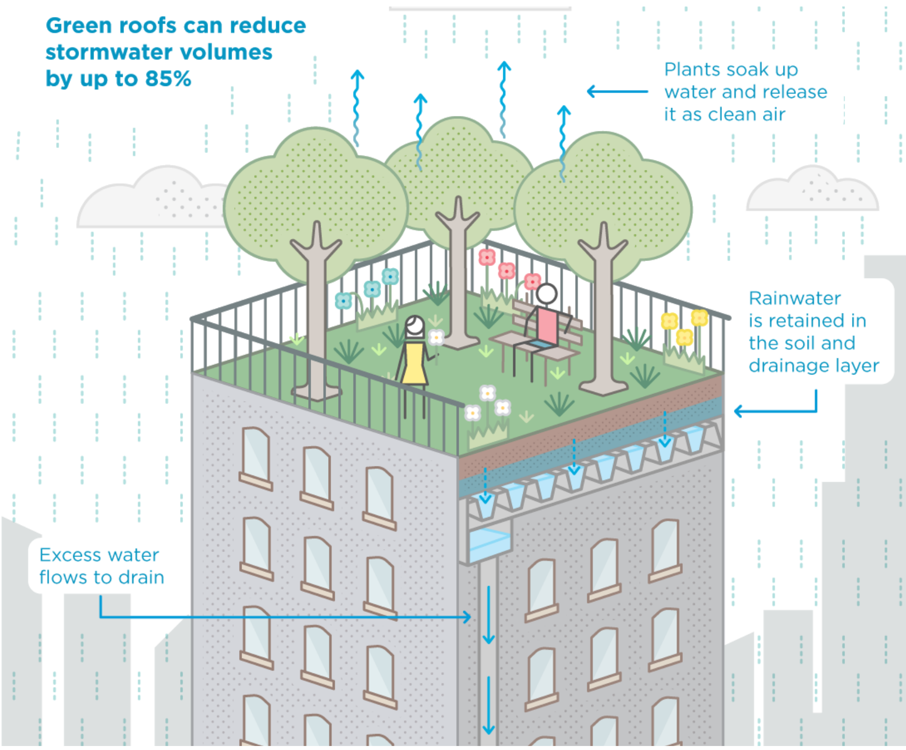

Fig. 2-14 A simplified example of drainage for an urban building. (Source: Beaudoin (2024), p. 2))

b.b. Biological and vital functions

- **Improves Habitat:** Green roof vegetation enhances wildlife access and habitats in urban areas, supporting biodiversity and providing valuable habitats for various flora and fauna[1].

b.c. Economic functions

- **Food production:**
  Green roofs provide opportunities for urban agriculture[2].

- **Enhancement of market value of building:**
  Green roofs can increase the monthly rental value of a building by 16.2%, while intensive and extensive roofs increase property value by 5%-8% and 2%-5%, respectively[3].

[1] Beaudoin, 2024, *Elevating Urban Landscapes: How Green Roofs Enhance Biodiversity and Address Climate Change in California*, pp. 26–28; Dasuni et al., 2022, *Green roof as a technology towards sustainability: a perspective of benefits offered.*, p. 524

[2] U.S. EPA, 2010, *The Value of Green Infrastructure: A Guide to Recognizing Its Economic, Environmental and Social Benefits.*, p. 5

[3] Dasuni et al., 2022, *Green roof as a technology towards sustainability: a perspective of benefits offered.*, p. 524

b.d. Social and humanitarian functions

- **Improved Human Health and Comfort:**
  Green roofs have the potential to improve indoor comfort and reduce heat stress caused by heat waves[1]. They also improve public health by cleaning the surrounding environment and providing noise absorption and sound insulation, thereby enhancing the comfort of occupants[2].

- **Absorption of urbanized noise:**
  Green roofs can significantly reduce noise levels from 10-20 dB compared to conventional roofs, with the type of vegetation significantly affecting noise absorption[3], as soil and vegetation help in reducing local noise pollution[4].

- **Enhancing the aesthetic appearance of the building:**
  Green roofs in buildings attract users, but their aesthetic appeal is subjective, with extensive types potentially having less attraction compared to other green roof type[5].

- **Enhanced Quality of Life:**
  Green roofs provide outdoor recreational spaces for residents and improve community interactions, thereby enhancing social capital[6]. They offer a unique view of rooftop gardens, and public access, and can improve the overall quality of life for residents of taller buildings[7].

2.7.3. Cool Roofs

Cool roofing products that use reflective and emissive materials can help reduce heat islands caused by hot roofs in cities and suburbs[8]. the surface temperatures of the cool roofs stay below 50˚C while surface

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[1] Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies - Green roofs*, p. 8

[2] Dasuni et al., 2022, *Green roof as a technology towards sustainability: a perspective of benefits offered.*, p. 522; Ogaili & Sailor, 2015, *Measuring the Effect of Vegetated Roofs on the Performance of Photovoltaic Panels in a Combined System*, p. 29

[3] Beaudoin, 2024, *Elevating Urban Landscapes: How Green Roofs Enhance Biodiversity and Address Climate Change in California*, p. 25,26; Dasuni et al., 2022, *Green roof as a technology towards sustainability: a perspective of benefits offered.*, p. 522

[4] U.S. EPA, 2010, *The Value of Green Infrastructure: A Guide to Recognizing Its Economic, Environmental and Social Benefits.*, p. 5

[5] Dasuni et al., 2022, *Green roof as a technology towards sustainability: a perspective of benefits offered.*, p. 522; Ogaili & Sailor, 2015, *Measuring the Effect of Vegetated Roofs on the Performance of Photovoltaic Panels in a Combined System*, p. 9

[6] U.S. EPA, 2010, *The Value of Green Infrastructure: A Guide to Recognizing Its Economic, Environmental and Social Benefits.*, p. 5

[7] Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies - Green roofs*, p. 8

[8] Gregory Chin et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Cool Roofs*, p. 1

temperatures of darker roofs reach 90˚C or higher[1]. Cool Roofs can reduce air temperature by 1.3 °C and thermal stress by 2-2.5 °C[2]. Solar reflectance and thermal emittance play an important role in reducing the combined temperature effect of these materials[3]:

- Solar Reflectance, or albedo: Cool roofs have high surface reflectance[4], traditional roofing materials have low reflectance, absorbing 85-95% of energy, while the coolest materials have high reflectance, absorbing and transferring 35-55% of energy, especially in visible and infrared wavelengths[5] (Fig. 2-15).

Fig. 2-15 Effect of Albedo on Surface Temperature. (Source: Gregory Chin 2008, p. 4)

- Thermal Emittance: Surfaces exposed to radiant energy heat up until they reach thermal equilibrium, at which point they emit the same amount of heat as they receive. Surfaces with high emittance reach thermal equilibrium at lower temperatures[6].

Fig. 2-16 describes the flow of radiant energy as heat between the sun, roof, and wall surfaces, building interior, and surroundings. The higher the solar reflectance, the more solar energy is reflected away from the surface. Some of the solar energy is absorbed by the surface as heat. The higher the thermal emittance, the more absorbed heat is radiated away from the surface[7].

[1] Ogaili & Sailor, 2015, *Measuring the Effect of Vegetated Roofs on the Performance of Photovoltaic Panels in a Combined System*, p. 6

[2] Mughal, Li, & Norford, 2020, *Urban heat island mitigation in Singapore: Evaluation using WRF/multilayer urban canopy model and local climate zones*, p. 2

[3] Gregory Chin et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Cool Roofs*, p. 2

[4] Mughal et al., 2020, *Urban heat island mitigation in Singapore: Evaluation using WRF/multilayer urban canopy model and local climate zones*, p. 16

[5] Gregory Chin et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Cool Roofs*, p. 3

[6] Ibid.

[7] Cool Roof Rating Council, 2021, *Reducing Urban Heat with Cool Roofs and Solar-Reflective Walls How Can We Mitigate Urban Heat Islands ?*, p. 2

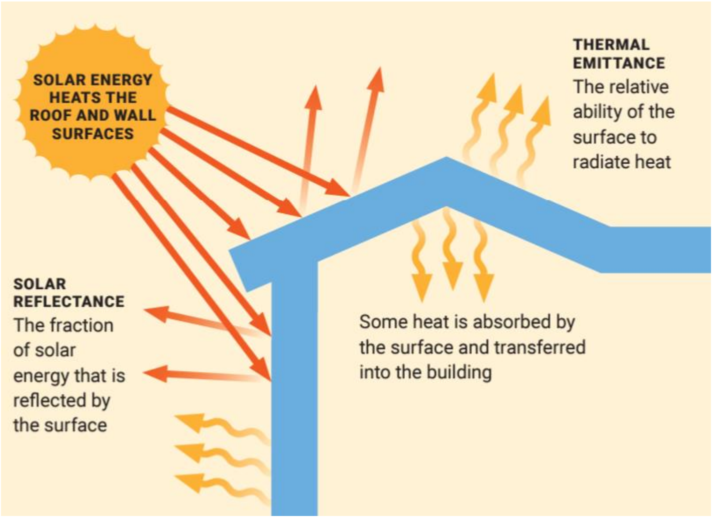

Fig. 2-16 The flow of radiant energy as heat between the sun, roof surface, building interior, sky and surroundings. (Source: Cool Roof Rating Council, (2021), https://coolroofs.org/documents/CRRC-Poster_PRINT.pdf, accessed 13/12/2024)

The surface temperatures of the white (cool) roofs stay below 50˚C while surface temperatures of darker (Conventional) roofs reach 90˚C or higher[1]. Reduced surface temperatures from cool roofs lower air temperature. Conventional roofs have low reflectance but high thermal emittance, with summer temperatures ranging from 74 to 85°C. Metallic or bare metal roofs have a high reflectance and a low thermal emittance, warming to 66-77°C, while cool roofs with high reflectance and emittance reach peak temperatures of 43-46°C[2].

a. Cool Roof Types:

Cool roofs are classified into two types: low-sloped roofs and steep-sloped roofs they differ in used roofing materials[3]:

- **Low-Sloped Cool Roofs:**

  Low-sloped roofs are flat with only enough incline for drainage, commonly used in commercial, industrial, warehouse, office, retail, multi-family, and single-family homes[4] (Fig. 2-17). The material used is the built-up roofing or a membrane, the primary cool roof options are coatings and single-ply membranes[5] (Fig. 2-18).

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[1] Ogaili & Sailor, 2015, *Measuring the Effect of Vegetated Roofs on the Performance of Photovoltaic Panels in a Combined System*, p. 6

[2] Gregory Chin et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Cool Roofs*, p. 4

[3] Aboulnaga et al., 2024, *Livable cities - Urban Heat Islands Mitigation for Climate Change Adaptation Through Urban Greening*, p. 334; Gregory Chin et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Cool Roofs*, pp. 5–7

[4] Gregory Chin et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Cool Roofs*, p. 5

[5] Ibid.p. 5,6; Urban & Roth, 2010, *Guidelines for selecting cool roofs*, p. 8

Fig. 2-17 Low-Sloped Cool Roof. (Source: Gregory Chin 2008, p. 5)

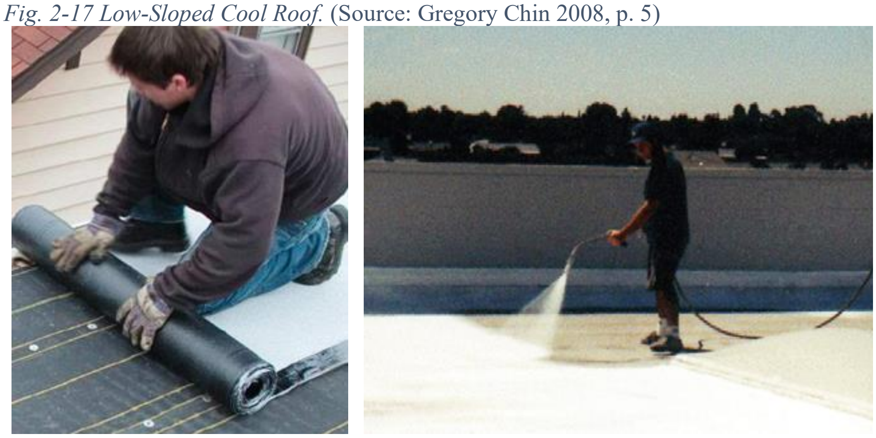

Fig. 2-18 Left: cool single-ply membrane roof is unrolled (Source: Urban & Roth (2010), p.8), Right: Cool Coating Being Sprayed onto a Rooftop (Source: Gregory Chin 2008, p. 5)

- **Steep-Sloped Cool Roofs:**

  Steep-sloped roofs are common in residential and commercial buildings and are usually visible from the street. Asphalt shingles, metal roofing, tiles, and shakes are common roofing materials for steep-sloped roofs[1] (Fig. 2-19), but their solar reflectance is generally lower than that of low-sloped cool roofs[2].

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[1] Gregory Chin et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Cool Roofs*, p. 6,7; Urban & Roth, 2010, *Guidelines for selecting cool roofs*, p. 8,9

[2] Gregory Chin et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Cool Roofs*, p. 6,7

Fig. 2-19 left: Conventional and Cool Colored Tiles, right: Cool Metal Roofing. (Source: Gregory Chin 2008, p. 9)

b. Benefits of Cool Roofs:

Cool roofs provide indoor comfort as they reflect solar radiation and reduce energy and air pollution[1]. In addition to environmental and natural functions, Social and humanitarian functions.

b.a. Environmental and natural functions

- **Reduced Energy Use:**
  Cool roofs have the potential to reduce urban temperatures and building energy consumption for cooling[2] as it reduces heat transfer, resulting in cooler, more comfortable conditions, and reduced energy consumption[3].
- **Reduced Air Pollution and Greenhouse Gas Emissions:**

Cool roofs help to reduce urban smog by reducing energy consumption and pollutant emissions during the summer[4]. As well as reducing carbon emissions by lowering the need for fossil-fuel[5].

b.b. Social and humanitarian functions

Improved Human Health and Comfort: Cool roofs reduce building air temperatures and help prevent heat-related illnesses and deaths[6]. Over 10 years, a 20% increase in surface reflectance was

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[1] LaFrance, 2010, *Cool roofs are ready to save energy, cool urban heat islands, and help slow global warming.*; Ogaili & Sailor, 2015, *Measuring the Effect of Vegetated Roofs on the Performance of Photovoltaic Panels in a Combined System*, p. 7

[2] LaFrance, 2010, *Cool roofs are ready to save energy, cool urban heat islands, and help slow global warming.*, p. 1; Macintyre & Heaviside, 2019, *Potential benefits of cool roofs in reducing heat-related mortality during heatwaves in a European city*, p. 431

[3] Gregory Chin et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Cool Roofs*, p. 8

[4] Ibid.p. 10; Macintyre & Heaviside, 2019, *Potential benefits of cool roofs in reducing heat-related mortality during heatwaves in a European city*, p. 431

[5] LaFrance, 2010, *Cool roofs are ready to save energy, cool urban heat islands, and help slow global warming.*, p. 1

[6] Gregory Chin et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Cool Roofs*, p. 11; Ogaili & Sailor, 2015, *Measuring the Effect of Vegetated Roofs on the Performance of Photovoltaic Panels in a Combined System*, p. 7

found to reduce heat-related mortality by between 5% and 21% in US cities[1].

Cool roofs reflect solar energy year-round, which can be a disadvantage in the winter as they reflect away desirable wintertime heat gain[2].

2.7.4. Cool Pavement

Cool pavements refer to paving materials that reflect more solar energy and enhance water evaporation to remain cooler. Their effectiveness depends on their ability to decrease surface temperature[3], to reduce urban heat islands caused by increased temperatures on paved surfaces[4]. Fig. 2-20 shows the road with light and dark segments, The infrared image shows that the light segment (bottom) is about 17°C cooler than the dark segment (top)[5].

Fig. 2-20 Thermal infrared (left) and visible (right) images of a road with light and dark segments. (Source: Rupard M 2019, p. 20)

Pavement temperatures are affected by properties like solar energy, solar reflectance, material heat capacities, surface roughness, heat transfer rates, thermal emittance, and permeability[6].

a. Cool Pavement Types:

The effectiveness of cool pavements is determined by their ability to reduce surface temperature through three approaches: high reflectance in albedo (Fig. 2-20), and a high emissivity in infrared radiation

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[1] Macintyre & Heaviside, 2019, *Potential benefits of cool roofs in reducing heat-related mortality during heatwaves in a European city*, p. 432

[2] Gregory Chin et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies Cool Roofs*, p. 9

[3] Qin, 2015, *A review on the development of cool pavements to mitigate urban heat island effect*, p. 446

[4] Bruce Ferguson et al., 2012, *Reducing Urban Heat Islands: Compendium of Strategies, Cool Pavements*, p. 1

[5] Rupard, 2019, *Urban Heat Islands: Causes, Impacts, & Mitigation*, p. 20

[6] Bruce Ferguson et al., 2012, *Reducing Urban Heat Islands: Compendium of Strategies, Cool Pavements*, p. 3

(reflective pavements), or they use evaporative cooling to reduce their surface temperature[1]:

- Solar Reflectance, or albedo: Albedo affects pavement temperatures below the surface by reducing the amount of heat available to be transferred into the pavement. Conventional paving materials, such as asphalt and concrete, absorb 95-60% of the energy that reaches them.
- Thermal Emittance: The ability of a material to emit heat per unit area at a given temperature.
- Permeable pavements, which were originally designed for stormwater management, are now being considered as potential cool pavements. These pavements allow air, water, and water vapour to enter the voids, lowering temperatures through evaporative cooling, much like the vegetated land cover. Permeable pavement systems may include grass or low-lying vegetation.

Table 2-5 shows the types of cool pavements[2].

Table 2-5 Cool Pavement Types. (Source: Qin Y (2015), p. 446,447)

Modification	***Cool techniques***	***Types***	***Construction***
Absorption	Reduce heat absorptivity by reflecting solar radiation to the sky	Reflective asphalt pavement	Surface treatments or reconstruction
		Reflective concrete pavement	
	Make the surface reflective in hot weather and absorptive in cold weather	Thermochromic pavement with doped reflective pigments (Fig. 2-21)	
Storage	Extract heat from the pavement and reduce surface temperature	Heat-harvesting pavement	Reconstruction
	Reduce surface temperature by increasing conductivity heat	Phase change material-impregnated pavement and high-conductive pavement	
Evaporation	Increase latent heat release	Porous pavement, permeable pavement, and pervious pavement (Fig. 2-22)	Reconstruction
		Water-retentive pavement	

[1] Ibid.p. 3,6,8; Kappou et al., 2022, *Review Cool Pavements: State of the Art and New Technologies*, pp. 4-6,17; Lima et al., 2023, *Mitigation of Urban Heat Island Effects by Thermochromic Asphalt Pavement*, p. 1

[2] Qin, 2015, *A review on the development of cool pavements to mitigate urban heat island effect*, p. 446,447

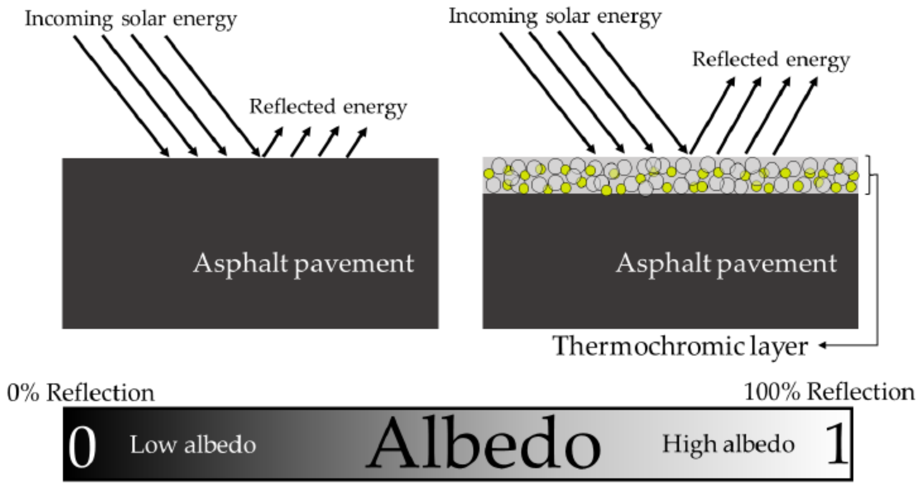

Fig. 2-21 Asphalt pavement with thermochromic ability. (Source: Lima et al., (2023), p.3)

b. Benefits of Cool Pavements:

Cool pavements work as cool roofs, but it is more effective in outdoor urban areas, in addition to environmental, economic functions, social and humanitarian functions.

b.a. Environmental and natural functions

- **Reduced Energy Use**

  Increased reflectance in reflective pavements reduces air temperature leading to reduced energy consumption[1].

- **Air Quality and Greenhouse Gas Emissions**

  By reducing energy demands, air pollution and greenhouse gas emissions decrease[2], improving urban air quality, Reflective pavements reduce air conditioning, CO2 emissions, smog, and ozone formations by lowering near surface temperatures and suppressing radon formation chemical reactions[3].

- **Water Quality and Stormwater Runoff**

  Permeable pavements (Fig. 2-22) can reduce surface temperatures by 2-4ºC, reducing stormwater runoff, re-charging

[1] Bruce Ferguson et al., 2012, *Reducing Urban Heat Islands: Compendium of Strategies, Cool Pavements*, p. 23

[2] Ibid.

[3] Qin, 2015, *A review on the development of cool pavements to mitigate urban heat island effect*, p. 453

groundwater and reducing thermal shock to aquatic life in waterways, compared to conventional asphalt paving[1].

Fig. 2-22 Porous Asphalt (left), Permeable Interlocking Concrete Pavement (right). (Source: David K. Hein 2013, p. 1)

b.b. Economic functions

Increased Pavement Life and Waste Reduction

Reducing pavement surface temperatures can prevent premature failure of asphalt pavements and slow ageing in concrete pavements, thereby reducing stress and cracking[2]. The porous structure reduces tire-road interaction and noise generation, enhancing tire load noise and providing better tire-road resistance after rainy events[3].

b.c. Social and humanitarian functions

- **Quality of Life[4]**

- Nighttime illumination

Reflective pavements (Fig. 2-23) can improve nighttime visibility, potentially reducing lighting requirements and saving money and energy.

- Comfort improvements

Reflective and permeable pavements can enhance comfort by reducing surface and near-surface air temperatures in areas where people congregate, and children play.

- Safety

[1] Bruce Ferguson et al., 2012, *Reducing Urban Heat Islands: Compendium of Strategies, Cool Pavements*, p. 23,24; Qin, 2015, *A review on the development of cool pavements to mitigate urban heat island effect*, p. 453

[2] Bruce Ferguson et al., 2012, *Reducing Urban Heat Islands: Compendium of Strategies, Cool Pavements*, p. 24

[3] Qin, 2015, *A review on the development of cool pavements to mitigate urban heat island effect*, p. 453

[4] Bruce Ferguson et al., 2012, *Reducing Urban Heat Islands: Compendium of Strategies, Cool Pavements*, p. 24; Ismael, Alias, Haron, Zaidan, & Abdulghani, 2024, *Mitigating Urban Heat Island Effects: A Review of Innovative Pavement Technologies and Integrated Solutions*, pp. 15–16; Qin, 2015, *A review on the development of cool pavements to mitigate urban heat island effect*, p. 453

Permeable roadway pavements improve safety by reducing vehicle water spray, increasing traction for better tire road resistance, and providing better nighttime driving visibility by draining water that causes glare.

Fig. 2-23 Cool pavement coating was applied to a street in Los Angeles. (Source: Rupard 2019, p. 21)

According to Oliveira, Andrade, & Vaz[1] The study in Lisbon analyzed the cooling effect of green spaces in urban areas, revealing that the garden was cooler than surrounding areas, in the sun or shade. The highest variation was 6.9°C in air temperature and 39.2°C in mean radiant temperature. Factors such as low wind speed, sun exposure, and urban geometry contributed to these variations. The study suggests that green spaces can help mitigate Urban Heat Islands and create a cooling effect in the face of climate change.

A study in Chicago compared summertime surface temperatures on a green roof to those on a neighboring building. On an August afternoon in the early afternoon, with temperatures in the 90s, the green roof surface temperature ranged from 33 to 48°C, while the adjacent building's dark, conventional roof was 76°C. The temperature of the near-surface air above the green roof was about 4°C cooler[2] (Fig. 2-24).

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[1] Oliveira, Andrade, & Vaz, 2011, *The cooling effect of green spaces as a contribution to the mitigation of urban heat: A case study in Lisbon*

[2] Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies - Green roofs*, p. 3

Fig. 2-24 Temperature Differences between a Green and Conventional Roof. (Source: Ryan Bell 2008, p.4)

According to a numerical study[1] investigates the urban heat island effect in a tropical city, Singapore using weather research and forecasting model (WRF) in April–May 2007 and 2008, It was found that cool roofs reduce near-surface air temperature during the day and green vegetation reduces it at night. Green vegetation also improves human thermal comfort in the early morning, indicating that it is more effective at mitigating overnight UHI.

A case study of the application of cool pavements in a dense urban area in Athens' Marousi[2]. The study involved the restoration of a 16,000 m^2 area with new high-reflectivity pavements, green spaces, and earth-to-air heat exchangers. It was estimated that replacing conventional pavements with cool pavements could reduce the region's maximum ambient temperature by 1.2 to 2°C.

According to Santamouris et al.[3] a review of 220 real-scale urban rehabilitation projects based on field experiments and numerical simulations. Fig. 2-25 shows the reductions of average and maximum ambient temperatures observed in different projects with the use of UHI mitigation strategies: reflective pavements, cool roofs, green infrastructure (trees and green roofs, trees and grass, and grass and green roofs), and water-related (pools, ponds, evaporative towers, sprinklers, foundations, and their combinations).

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[1] Li & Norford, 2016, *Evaluation of cool roof and vegetations in mitigating urban heat island in a tropical city, Singapore*

[2] Santamouris et al., 2012, *Improving the microclimate in a dense urban area using experimental and theoretical techniques - The case of Marousi, Athens*

[3] Santamouris et al., 2017, *Passive and active cooling for the outdoor built environment – Analysis and assessment of the cooling potential of mitigation technologies using performance data from 220 large scale projects*

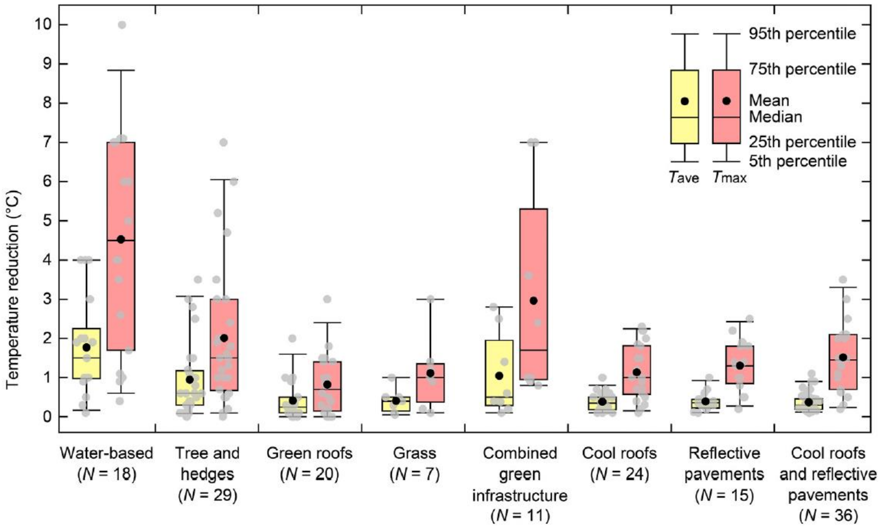

Fig. 2-25 The cooling effect (reductions in average and maximum temperatures) of different UHI mitigation strategies based on Santamouris et al.[1] *Note: N is the number of projects reviewed in each category,* T_{ave} *and* T_{max} *are average and maximum temperatures, respectively, and circles in grey show the results of individual projects.* (Source: Wang 2021, p. 9)

From Fig. 2-25 it was found that water-based and combined green infrastructure has the highest cooling effect.

2.8. Conclusion

The urban heat island (UHI) phenomenon is a local climatic issue that has a direct negative impact on the global climate, exacerbated by rapid urbanization and climate change. The phenomena is characterized by higher temperatures in cities than in areas around them, it is caused by a variety of factors, including impervious surfaces, reduced vegetation, anthropogenic heat emissions, specific urban designs that trap heat, pollutants and weather conditions. The UHI phenomenon poses significant environmental, social, economic, and biological challenges to urban areas worldwide. UHI phenomena can lead to death and serious diseases, therefore governments have to adopt mitigation strategies to mitigate the effect of UHI, such as:

- Promoting vegetation and green spaces in urban areas can provide shade, reduce surface and air temperatures, and enhance the overall quality of life.
- Enhance urban geometry by optimizing building dimensions and spacing to improve wind flow and reduce heat accumulation.

[1] Ibid.

- Increase green roof adoption to reduce rooftop temperatures and improve insulation, particularly in densely populated urban areas.
- Implement cool pavements by using reflective and permeable materials to reduce surface temperatures in wide streets or areas with limited shade.
- Install reflective and high-emittance materials on rooftops to reduce heat gain.
- Utilizing permeable surfaces can improve stormwater management and provide a cooling effect due to evaporation.

As for existing cities it has to be redesigned to include the adopted strategy. Mitigation strategies address the diverse scales at which UHI presents, targeting both individual buildings and entire urban landscapes illustrated in Fig. 2-26.

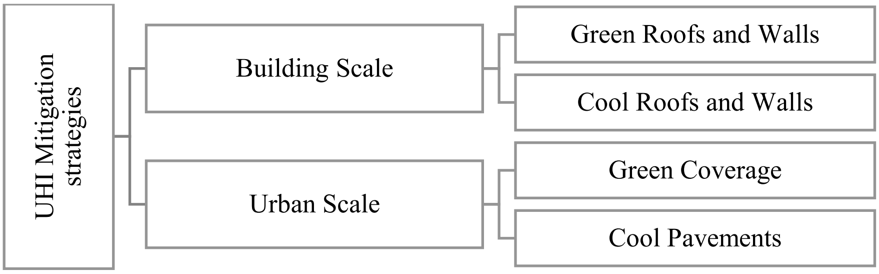

Fig. 2-26 Urban Heat Island Mitigation Strategies. (Source: Author)

- Building Scale Mitigation

Green and cool roofs reduce surface temperatures, increase energy efficiency, reduce cooling demands, and improve indoor comfort, thereby mitigating UHI effects in dense urban areas.

- Urban Scale Mitigation

Urban planning should incorporate green infrastructure like green spaces and permeable pavements for cooling, biodiversity enhancement, air and water quality improvement, and community resilience against extreme weather events.

Table 2-6 Summaries the functions of each strategy.

Table 2-6 Mitigation strategies functions (Source: Author)

		Building scale		Urban scale	
		Green roof	Cool roofs	Green coverage	Cool pavements
Environmental functions	Reduced Energy Use	✓	✓	✓	✓
	Air Quality	✓	✓	✓	✓
	Stormwater Management and Water Quality	✓	-	✓	✓
Biological functions	Improves Habitat	✓	-	✓	-
Economic functions	Reduced Pavement Maintenance Costs	-	-	✓	-
	Food Production	✓	-	✓	-
	Enhancement of Market Value of Building	✓	-	✓	-
	Increase pavement life	-	-	-	✓
Social functions	Improved Human Health	✓	✓	✓	-
	Enhanced Quality of Life	✓	-	✓	✓
	Noise Reduction	✓	-	✓	-
	Enhance the Aesthetic Appearance of the Building	✓	-	-	-

From Table 2-6 Green coverage and green roofs have the most environmental functions third cool pavements. Green infrastructure which includes vegetation, green roofs, and permeable surfaces, is a natural solution to urban overheating. Its multifunctional benefits go beyond temperature regulation and address larger problems like climate adaptation, stormwater management, and ecological restoration.

Collaboration between building-scale and urban-scale strategies emphasizes the importance of overall approaches to UHI mitigation. The following chapter will discuss how green infrastructure serves as a combining framework, connecting these scales and allowing cities to adapt sustainably to climate change. By focusing on nature-based solutions, urban planning may improve the built environment into a harmonious blend of ecological functionality and human livability.

CHAPTER 3

GREEN INFRASTRUCTURE

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3.1. Introduction

Urbanization is projected to accelerate significantly over the next 30 years, with cities expected to accommodate more than two-thirds of the global population by 2050[1]. Anthropogenic activities, including greenhouse gas emissions and changes in land use and land cover, profoundly impact the climate. Poorly planned urban development can exacerbate deforestation, biodiversity loss, habitat destruction, and the Urban Heat Island (UHI) effect, which increases temperatures in cities compared to surrounding rural areas. However, integrating nature-based solutions, such as green infrastructure, into urban planning can play a vital role in mitigating the UHI effect while enhancing city resilience and sustainability[2].

Green infrastructure is a new term, but it is not a new idea. The concept itself has deep roots, evolving from two key ideas: connecting parks and green spaces to benefit people and linking natural areas to support biodiversity and mitigate habitat fragmentation[3]. Green infrastructure operates across different scales, from individual buildings to entire urban areas, addressing issues such as the Urban Heat Island (UHI) effect by incorporating cooling strategies like green roofs, walls, and urban tree canopies. This chapter defines green infrastructure, The challenges faced by urban areas, the principles of GI, the elements, and functions of GI, additionally, the applications for implementing the concept effectively at both the building and urban scale.

3.2. Concept of Green Infrastructure (GI)

Green infrastructure is "an interconnected network of green space that conserves natural ecosystem values and functions and provides associated benefits to human populations." GI is a term that means different things to different people depending on the context[4], The concept of GI definitions can be split into two categories:

a. A green network:

Green infrastructure is a network of connected green areas that preserves the values and functions of natural ecosystems while

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[1] United Nation, 2018, *68% of the world population projected to live in urban areas by 2050, says UN*

[2] Maritza Carlsson, 2021, *Exploring the potential of Green Infrastructure to enhance urban resilience as part of the 2040 Development Plan La Paz, Bolivia*, p. 2

[3] Benedict Mark A. & McMahon Edward T., 2002, *Green Infrastructure: Smart Conservation for the 21st Century*, p. 13

[4] Ibid.p. 12

benefiting human populations[1]. It includes urban green spaces such as greenways, parks, rain gardens, street trees, and bioswales, which provide various social and ecological benefits. The interconnectedness of green spaces enhances these benefits while also conserving existing natural ecosystems[2].

b. Low-impact development (LID) technology or sustainable stormwater infrastructure:

Low Impact Development (LID) is defined as a land development strategy for managing stormwater at the source through decentralized micro-scale control measures[3]. The U.S. Environmental Protection Agency (EPA) defines green infrastructure as "an adaptable term used to describe an array of products, technologies, and practices that use natural systems or engineered systems that mimic natural processes to enhance overall environmental quality and provide utility services."[4].

Both definitions identify green infrastructure as multifunctional, which means that it can provide a variety of social and environmental benefits even if it is installed for a specific purpose[5].

Urban Green Infrastructure (UGI) planning can be defined as a strategic planning approach that aims to develop networks of green and blue spaces in urban areas that are designed and managed to provide a wide range of ecosystem services and other benefits at all spatial scales. Because of its integrative, multifunctional approach, UGI planning can address a wide range of urban challenges; biodiversity conservation, climate change adaptation, green economy support, and social cohesion improvement[6].

3.3. Green Infrastructure Elements

Green space typology consists of 44 elements organized into eight groups[7]:

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[1] Ibid.

[2] Lau, 2018, *Stacking Green Infrastructure Benefits: A Spatial Multi-Criteria Approach to Green Infrastructure Planning in Seattle, Washington.*, p. 5

[3] Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 24

[4] Lau, 2018, *Stacking Green Infrastructure Benefits: A Spatial Multi-Criteria Approach to Green Infrastructure Planning in Seattle, Washington.*, p. 5

[5] Ibid.p. 4

[6] Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 3

[7] Anjali Saraswat & Satish Pipralia, 2020, *System Dynamics Approach For Planning Green Infrastructure In Cities*, p. 332; Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 6

a. Building Greens:

Green spaces and areas that surround a building's roof, and walls, or are enclosed within the structure[1]. (Table 3-1)

Table 3-1 Building Green Element Description. (Source: Braquinho et al. (2015), p. 18,19)

UGI element	***Description***	***Example***
Balcony green	Potted plants on balconies and terraces.	
Ground-based green wall	Ground-grown climbing plants used for decorative purposes and occasionally for food production.	
Facade-bound green wall	Plants growing in façade bound substrate.	
Extensive green roof	Roof vegetation on thin substrates requires minimal irrigation and maintenance and typically features mosses, succulents, herbs, and grasses.	
Intensive green roof	Roof vegetation on a thick substrate, supported by irrigation and management, is established either artificially or naturally.	
Atrium	Green spaces within or enclosed by a building, primarily featuring decorative plants.	

[1] Braquinho et al., 2015, *A Typology Of Urban Green Spaces, Eco-System Services Provisioning Services And Demands*, p. 18,19

b. Green Space Connected to Grey Infrastructure

Outdoor green areas linked to transportation, stormwater infrastructure, and buildings[1]. (Table 3-2)

Table 3-2 Green Space Connected to Grey Infrastructure Element Description. (Source: Braquinho et al. (2015), pp. 19-21)

UGI element	***Description***	***Example***
Bioswale	A gently sloped, vegetated pit designed to filter surface runoff.	
Tree alley and street tree, hedge	Trees are planted along roads and paths, either individually or in rows, as well as hedges bordering roads or paths.	
Street green and green verge	Non-tree verges, primarily consisting of shrubs or grasses, along roads or other built or natural features.	
Private Garden	Areas around private houses cultivated for ornamental purposes and/or non-commercial food production.	
Railroad bank	Green space is located alongside railroads.	
Green playground, school grounds	Green spaces intended for outdoor play or educational activities.	

c. Riverbank Green:

Green space sideways the rivers, streams, and canals, usually with foot or bike paths[2] (Fig. 3-1).

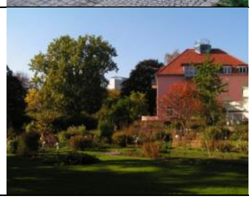
[1] Ibid.pp. 19–21

Fig. 3-1 Riverbank Green. (Source: Braquinho et al. (2015), p. 21)

d. Parks and Recreation

Private or semi-private urban green spaces in recreation, mental and physical health, aesthetic appreciation, and inspiration[1]. (Table 3-3)

Table 3-3 Parks and Recreation Element Description. (Source: Braquinho et al. (2015), pp. 21-23)

UGI element	***Description***	***Example***
Large urban park	Large green areas within a city are designed for recreational use by the urban population, which may include features such as trees, grassy fields, playgrounds, water bodies, and ornamental beds.	
Historical Park/garden	Large urban parks with distinct management due to their heritage status.	
Pocket Park	Small park-like spaces around and between buildings, featuring ornamental trees and grass, that are publicly accessible.	
Botanical garden/ arboretum	Educational and decorative spaces planted with a wide variety of plant species.	

[2] Ibid.p. 21
[1] Ibid.

UGI element	Description	Example
Zoological garden	Area housing animals in cages and enclosures, often combined with planted trees, ornamental beds, and cultivated grass.	
neighborhood green space	Semi-public green spaces with grass, trees, and shrubs in multi-story residential areas.	
Institutional green space	Green spaces surrounding public and private institutions, as well as corporate buildings.	
Cemetery and churchyard	Burial grounds typically feature lawns, trees, and other ornamental plants.	
Green sports facilities	Intensively cultivated and fertilized grass turf designed to withstand frequent trampling for sports activities, such as golf courses and football fields.	
Camping areas	Green areas designated for camping.	

e. Community Spaces.

Gardened area for food production and recreation[1]. (Table 3-4)

Table 3-4 Community Spaces Element Description. (Source: Braquinho et al. (2015), p. 24)

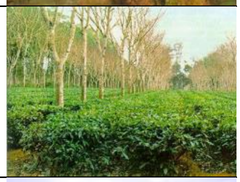
UGI element	Description	Example
Allotments	Small garden plots cultivated by various individuals for non-commercial food production and recreation	
Community gardens	A community garden space for growing food and recreational activities.	

[1] Ibid.p. 24

f. Agricultural Land

Large areas of land suitable for crop production, mixed agricultural and fruit production, or biofuel production[1]. (Table 3-5)

Table 3-5 Agricultural Land Element Description. (Source: Braquinho et al. (2015), p. 24,25)

UGI element	***Description***	***Example***
Arable land	Land that is regularly ploughed for crop production.	
Grassland	Grassland areas used for grazing animals or left as meadows.	
Tree meadow/ orchard	Fruit and nut trees, along with mixed agricultural and biofuel production.	
Biofuel production/ agroforestry	Land dedicated to the production of biofuels, such as short rotation coppice.	
Horticulture	Land dedicated to growing vegetables, flowers, berries, and other crops.	

g. Natural, semi-natural and feral areas

Green areas that are natural or semi-naturally created without the intervention of humans[2] (Table 3-6).

[1] Ibid.

[2] Ibid.pp. 25–27

Table 3-6 Natural, semi-natural and feral areas Element Description. (Source: Braquinho et al. (2015), pp. 25-27)

UGI element	*Description*	*Example*
Forest (e.g., remnant woodland, managed forests, mixed forms).	Natural or planted areas with dense tree vegetation.	
Shrubland	Natural or secondary shrubland areas, such as heath or macchia.	
Abandoned, ruderal and derelict areas	Recently abandoned areas, construction sites, and similar spaces with spontaneously occurring pioneer or ruderal vegetation.	
Rocks	Areas consisting of sparsely vegetated rocky terrain.	
Dunes	Sparsely vegetated sandy areas shaped by wind or water.	
Sandpit, quarry, open cast mine	Sites where topsoil and vegetation have been removed for resource extraction.	
Wetland, bog, fen, marsh	Areas with soil that is permanently or periodically saturated with water, supporting characteristic flora and fauna.	

h. Blue spaces

Natural or artificial water areas or land depressions formed by flowing water, but typically dry[1]. (Table 3-7)

Table 3-7 Blue spaces Element Description. (Source: Braquinho et al. (2015), p. 27)

UGI element	*Description*	*Example*
Lake, pond	Natural and artificial standing water bodies with non-saline water, hosting (semi)natural aquatic communities, and featuring either managed or natural banks.	
River, stream	Running waters, such as springs, streams, and temporary watercourses, with riverbanks that may be either artificial/managed or natural.	
Dry riverbed	A land depression formed by flowing water, typically dry, which can be either managed or unmanaged. It is usually rich in biodiversity and often used for recreational purposes.	
Canal	Artificial non-saline watercourses with engineered substrates.	
Estuary	The downstream section of the river is influenced by tidal effects, resulting in the mixing of freshwater and seawater.	
Delta	The landform at the mouth of a river, created by the deposition of sediment.	
Sea Coast	Contact areas (littoral zones) between the sea and land, featuring various characteristics such as sandy beaches, cliffs, and coastal dunes.	

[1] Ibid.p. 27

3.4. Principals of GI

mui These principles are essential for the success of green infrastructure initiatives[1]. They are divided into 4 key principals and 3 supportive ones illustrated in Fig. 3-2.

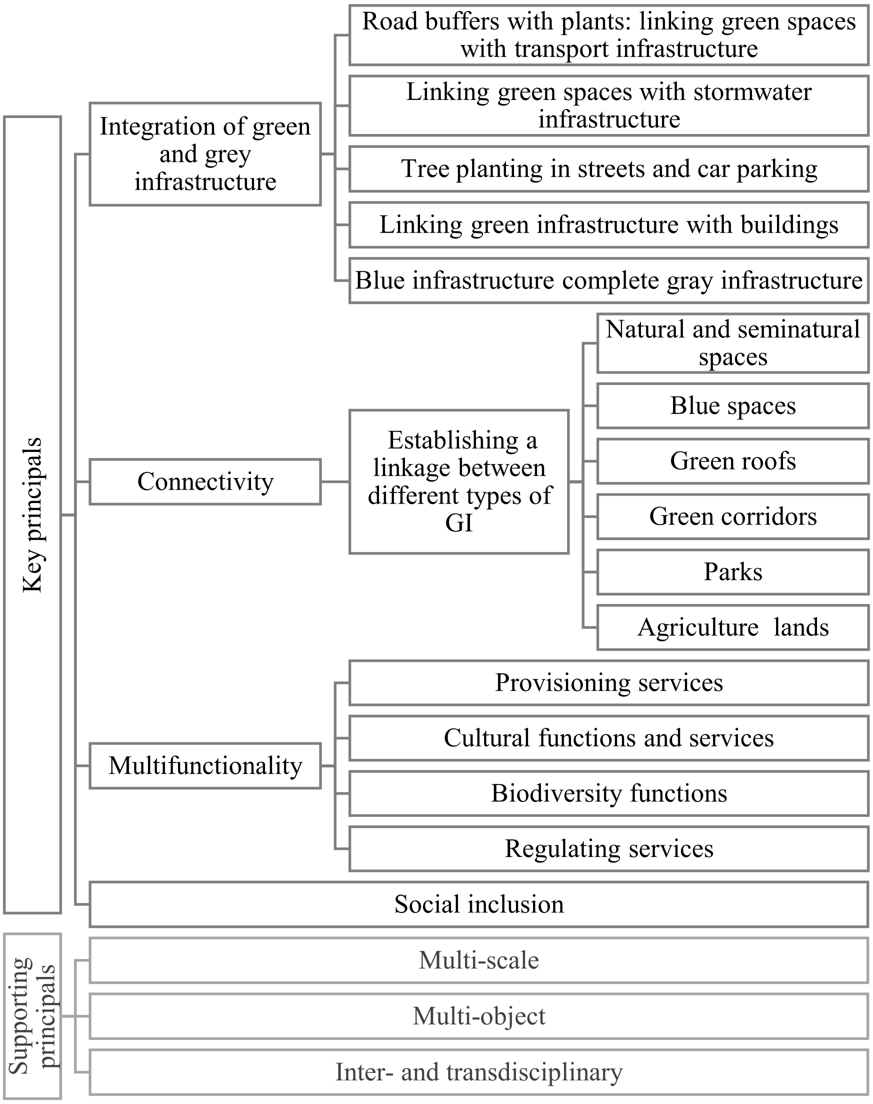


Fig. 3-2 Principals of Green Infrastructure. (Source: Author)

[1] Benedict Mark A. & McMahon Edward T., 2002, *Green Infrastructure: Smart Conservation for the 21st Century*, p. 16

3.5.1. Key Principals

a. Integration of green and grey infrastructure

Urban green infrastructure planning aims to integrate and coordinate urban green spaces with other infrastructure, such as transportation systems and utilities. It aims to provide wider environmental, social, and economic benefits in addition to meeting primary infrastructure needs[1]. The concept of infrastructure consists of both natural and man-made elements, with a "green/grey" spectrum encompassing hybrid or semi-natural systems like cycle routes and suburban gardens.[2]

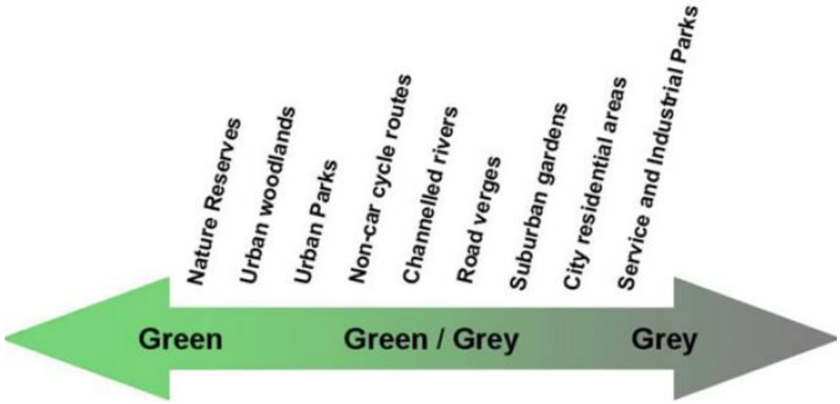


Fig. 3-3 The Grey-Green Continuum. (Source: Wesener & McWilliam, 2021, p.3)

b. Connectivity - establishing green space networks

UGI connectivity planning entails establishing and restoring links to support and protect processes, functions, and benefits that individual green spaces cannot provide on their own. Landscape connectivity can be defined as the extent to which the landscape facilitates or inhibits movement and flow[3], Fig. 3-4 show the UGI network made up of many different elements.

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[1] Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 23

[2] Wesener & McWilliam, 2021, *Integrated Urban Green and Grey Infrastructure*, p. 2

[3] Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 27; Neveen Youssef Azmy, 2020, البنية التحتية الخضراء وتأثيرها على العمران, p. 72

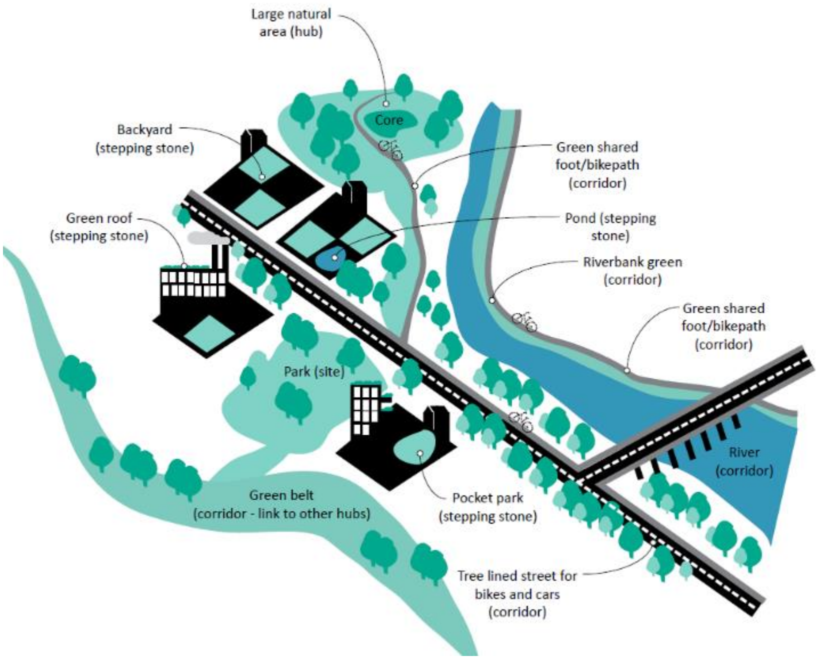

Fig. 3-4 An urban green infrastructure network is made up of many different elements that work together to help people move around the city. (Source: Hansen R et al. (2017) p. 28)

Successful urban planning for connectivity relies on a complete consideration of functional and structural features[1]:

- Functional connectivity: considers the characteristics and behaviour of wildlife and humans that interact with the overall landscape structure, such as habitat preferences, movement patterns, and the ability to adapt to changes in the environment.
- Structural connectivity: focuses on the physical elements that facilitate movement and access. This includes the design of roads, bridges, and other infrastructure that connect different parts of the urban landscape.

Both functional and structural connectivity are important for creating a sustainable and livable urban environment. The purpose of connectivity must be clearly defined ideally encompassing ecological, social, and abiotic movements and seeking synergies between them. Structural connectivity measuring is frequently based on the presence or absence, size, form, and shape of corridors and steppingstones[2].

[1] Albright et al., 2021, *Connectivity & Climate Change Toolkit*, p. 5; Curcic & Djurdjic, 2013, *The actual relevance of ecological corridors in nature conservation*, p. 2; Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 28

[2] Davies et al., 2015, *Green Infrastructure Planning And Implementation*, p. 42; Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 28

Connectivity can be measured using various indicators such as distances, frequency, density, or cost distance analysis. Changes to green corridors over time can be visualized using aerial photography archives and GIS software[1].

c. Multifunctionality – delivering and enhancing multiple functions and services.

Multifunctionality is ability to perform several functions and provide several benefits in the same spatial area[2], it aims to secure and expand UGI's ecological, socio-cultural, and economic benefits, considering the interdependence of various functions and services and the ability of urban green spaces to provide them. It also targets the social issues of demand and access to UGI[3].

Ecosystem services are important to multifunctionality, it refer to the benefits that humans derive from ecosystems, they are classified into four categories and represent the ecological, sociocultural, and economic dimensions of multifunctionality[4] (Table 3-8):

Table 3-8 The Four Categories of Ecosystem Services. (Source: Hansen R et al. (2017), p. 32)

Provisioning service	***Cultural functions and services***	***Biodiversity functions***	***Regulating services***
- Agricultural products - Gardening products - Game, fish - Consumable wild plants - Freshwater - Wood, pulp - Medicine	- Recreation - Nature contemplation - Aesthetics - Sense of place, heritage - Social encounters - Education + Science - Inspiration - Urban Structure - Mobility - Tourism	- Habitat (common species) - Habitat (rare species) - Wilderness - Native biodiversity - Structural diversity - Wildlife movement - Pollination	- Erosion control - Flood control - Water flow regulation - Ventilation/Wind buffer - Noise mitigation - Temperature regulation - Global climate regulation

[1] Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 26
[2] Madureira & Andresen, 2014, *Planning for multifunctional urban green infrastructures: Promises and challenges*, p. 1
[3] Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 31; Madureira & Andresen, 2014, *Planning for multifunctional urban green infrastructures: Promises and challenges*, p. 1
[4] Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 32

d. Social inclusion – collaborative and participatory planning

UGI planning aims for collaborative, socially inclusive processes. This means that planning processes are open to all and incorporate the knowledge and needs of diverse parties, with a focus on the most vulnerable. It aims to identify and balance the interests of various stakeholders to facilitate more equitable access to green space services. Initiatives to involve citizens in planning can result in outcomes that favor certain groups while discouraging others, and governing institutions should be able to listen to and balance a variety of interests, particularly for those who have difficulty accessing information[1].

3.5.2. Supporting Principals

a. Multi-scale:

UGI planning seeks to connect various spatial levels, from metropolitan regions to individual sites. Planners can create more holistic and effective strategies that address a variety of issues by considering the demands and characteristics of different scales. UGI planning, for example, could entail developing green infrastructure systems that not only improve local air and water quality but also serve as ecological corridors between urban areas and natural habitats. It could also entail developing policies that promote equitable access to green spaces across neighbourhoods and income levels[2].

b. Multi-object:

A green infrastructure network includes all types of urban green and blue spaces, regardless of ownership or origin. This means that public parks, private gardens, green roofs, and even street trees should all be considered part of the same network[3].

c. Inter- and transdisciplinary:

UGI planning seeks to bring together disciplines as well as science, policy, and practice. It combines knowledge and demands from various fields, such as landscape ecology, urban and regional planning, and

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[1] Ibid.p. 36

[2] Benedict Mark A. & McMahon Edward T., 2002, *Green Infrastructure: Smart Conservation for the 21st Century*, p. 16; Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 5

[3] Davies et al., 2015, *Green Infrastructure Planning And Implementation*, p. 46; Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 5

landscape architecture, and is best developed in collaboration with local governments and other stakeholders[1].

3.5. Functions of Green Infrastructure

The potential of urban green spaces had to be identified since they contribute to human health, species protection, and climate change (Fig. 3-5), and can help to tackle key urban challenges that cities face[2] in which UGI planning can help:

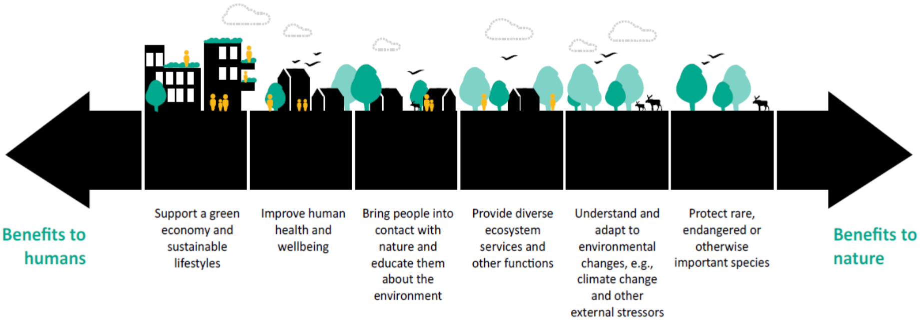

Fig. 3-5 Motives to protect urban biodiversity with benefits for nature and humans. (Source: Hansen R et al. (2017), p. 12.)

- With climate change adaptation by regulating the urban climate or reducing stormwater flooding[3].
- To increase the chances of conserving biodiverse environments and connecting people with them[4].
- To develop a green economy that improves social equity and human well-being while lowering environmental risks and resource depletion[5].
- To improve social cohesion by encouraging interactions between different social groups[6].

3.5.1. Environmental And Natural Functions

- **Temperature regulation**: provided by evapotranspiration and shading from vegetation and air flow through open spaces[7]:
  - The evaporation of water from plant surfaces cools the space around the plants, Plants with a large leaf area work

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[1] Benedict Mark A. & McMahon Edward T., 2002, *Green Infrastructure: Smart Conservation for the 21st Century*, p. 16,17; Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 5
[2] Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 7
[3] Neveen Youssef Azmy, 2020, البنية التحتية الخضراء وتأثيرها على العمران, p. 71
[4] Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 11
[5] Ibid.p. 14
[6] Ibid.p. 17
[7] Jones & Somper, 2014, *The role of green infrastructure in climate change adaptation in London*, p. 192

better in the evaporative cooling process than small leaf plants.
- Sun shading protects agricultural lands and other damages resulting from continuous exposure to direct solar radiation.
- GI design can control air movement and its performance inside and outside urban areas.

- **Carbon Sequestration:** Carbon dioxide is one of the main greenhouse gases, but it is readily sequestered from the atmosphere[1] as plants and trees absorb carbon dioxide from the atmosphere which improves air quality and maintains clean fresh air[2].
- **Air pollution mitigation:** Outdoor air pollution is more prevalent in cities, increasing the risk of heart disease, lung cancer, and respiratory diseases[3]. The stomata in the leaves of plants absorb harmful oxides such as sulfur dioxide, as well as particles suspended in the air that are deposited on the surfaces of plants. Where green spaces work to reduce pollutants in urban areas, especially public roads, as well as areas with high densities[4], e.g., Ventilation corridors increase the supply of fresh air and reduce pollution, while urban parks' cooling effect is enhanced when they are connected to a network[5].
- **Urban heat island effect mitigation:** green spaces in cities are effective ways to reduce urban heat island effects and provide relief to residents, as green structures enhance natural ventilation and cooling[6], e.g., Bike paths along powerlines' rights-of-way, gardens alongside railways, and street trees contribute to minimizing the heat island effect[7].
- **Increase thermal comfort of the buildings:** Plants reduce the amount of solar radiation that reaches the surface, lowering

[1] Lau, 2018, *Stacking Green Infrastructure Benefits: A Spatial Multi-Criteria Approach to Green Infrastructure Planning in Seattle, Washington.*, p. 8

[2] Ibid.; Neveen Youssef Azmy, 2020, البنية التحتية الخضراء وتأثيرها على العمران, p. 70

[3] Lau, 2018, *Stacking Green Infrastructure Benefits: A Spatial Multi-Criteria Approach to Green Infrastructure Planning in Seattle, Washington.*, p. 8

[4] Neveen Youssef Azmy, 2020, البنية التحتية الخضراء وتأثيرها على العمران, p. 70

[5] Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 27

[6] Dhir, 2021, *Evaluation of Urban Heat Island Effect in Cybercity, New Delhi Using a 3D Urban Microclimate Model: Envi-Met Item Type text; Electronic Thesis*, p. 27

[7] Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 28

surface temperatures and heat influx during hot weather months[1].

- **Noise absorption:** GI absorbs sound waves in urban spaces with intense noise to achieve human auditory comfort[2], e.g., Road buffers with vegetation can improve aesthetics while also reducing noise and air pollution[3].
- **Soil stabilization:** plants' roots help to improve soil strength, stability, and cohesion of the topsoil and prevent it from eroding[4].
- **Water quality:** The preservation of freshwater quality and supply by filtering sediments and pollutants through dense vegetation and soils (e.g., biofiltration swales)[5].
- **Stormwater management:** Reduced flooding risk by water storage and retention areas (e.g., ponds, canals, rain gardens), as well as the use of soil-covered surfaces over hard surfaces to facilitate drainage, reducing surface runoff, discharge, and slow tidal surges[6], e.g. In high-risk neighbourhoods, dispersed planting strips or rain gardens can improve the stormwater management capacity of traditional grey systems and buffer the effects of climate change[7].

3.5.2. Biological And Vital Functions:

- **Enhance species resilience:** The biodiversity of natural wildlife habitats has been fragmented and endangered because of urbanization. Green infrastructure connections or buffers are required to combat this and protect biodiversity[8]. Through:
  - The creation of diverse habitats and green corridors that allow species to easily migrate to new climate zones[9].

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[1] U.S. EPA, 2010, *The Value of Green Infrastructure: A Guide to Recognizing Its Economic, Environmental and Social Benefits.*, p. 4

[2] Neveen Youssef Azmy, 2020, البنية التحتية الخضراء وتأثيرها على العمران, p. 70

[3] Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 28

[4] Neveen Youssef Azmy, 2020, البنية التحتية الخضراء وتأثيرها على العمران, p. 70

[5] Benedict Mark A. & McMahon Edward T., 2002, *Green Infrastructure: Smart Conservation for the 21st Century*, p. 14; Jones & Somper, 2014, *The role of green infrastructure in climate change adaptation in London*, p. 192; Neveen Youssef Azmy, 2020, البنية التحتية الخضراء وتأثيرها على العمران, p. 70

[6] Benedict Mark A. & McMahon Edward T., 2002, *Green Infrastructure: Smart Conservation for the 21st Century*, p. 14; Jones & Somper, 2014, *The role of green infrastructure in climate change adaptation in London*, p. 192; Neveen Youssef Azmy, 2020, البنية التحتية الخضراء وتأثيرها على العمران, p. 70

[7] Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 28

[8] Lau, 2018, *Stacking Green Infrastructure Benefits: A Spatial Multi-Criteria Approach to Green Infrastructure Planning in Seattle, Washington.*, p. 9

[9] Jones & Somper, 2014, *The role of green infrastructure in climate change adaptation in London*, p. 192

- Habitat Improvement: A variety of animals, including birds, mammals, amphibians, reptiles, and insects, seek shelter in urban vegetation. Green infrastructure reduces erosion and sedimentation in small streams and washes, improving habitat[1].
- Habitat Connectivity: Large-scale green infrastructure, such as parks and urban forests, helps in wildlife movement and connectivity between habitats. e.g., The Loxahatchee Regional Greenways System protects the watershed and native ecosystems in Loxahatchee, Florida[2].

- **Wood and food production:** wood is produced from trees and forests, and food is produced through agricultural lands, which are an essential component of green infrastructure[3].
- **Biofuel production:** the use of vegetation as biofuel represents a form of energy represented by wood extracted from trees in addition to the waste of some crops[4].

3.5.3. Economic Functions

- **Increases property values:** Homes near open spaces, parks, and greenways have greater[5].
- **Cost-Effectiveness:** investing in green infrastructure is frequently less expensive than constructing traditional public works projects[6]. For example,[7]
  - In the 1990s, New York City saved $4-6 billion on new water filtration and treatment plants by spending about $1.5 billion to purchase and protect watershed land in the Catskill Mountains.
  - Similarly, by purchasing threatened floodplain properties and replacing them with greenways, Arnold, Missouri, has significantly reduced the need for costly disaster relief and flood damage repair efforts.

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[1] U.S. EPA, 2023, *Benefits of Green Infrastructure*
[2] Ibid.
[3] Neveen Youssef Azmy, 2020, البنية التحتية الخضراء وتأثيرها على العمران, p. 70
[4] Ibid.
[5] Benedict Mark A. & McMahon Edward T., 2002, *Green Infrastructure: Smart Conservation for the 21st Century*, p. 14
[6] Neveen Youssef Azmy, 2020, البنية التحتية الخضراء وتأثيرها على العمران, p. 71
[7] Benedict Mark A. & McMahon Edward T., 2002, *Green Infrastructure: Smart Conservation for the 21st Century*, p. 14,15

3.5.4. Social And Humanitarian Functions

- **Health Effects:** The city of Philadelphia's triple bottom line study found that increased tree canopy could reduce ozone and particulate pollution levels enough to significantly reduce mortality, hospital admissions, and work loss days. This could help reduce respiratory ailments, chest pain, coughing, asthma, and premature death[1].
- **Enhancing aesthetic vision and achieving psychological comfort:** It has been proved that access to green spaces has a positive influence on physical and mental health and wellness[2]. Trees along streets and roads, as well as green infrastructure, make the city a more appealing place to live and visit, reflecting the beauty of the landscape and attracting real estate and residential areas[3].
- **Enhancing the working and learning environments**: Open-air and public spaces that are connected to or belong to educational facilities improve performance and learning abilities. Green infrastructure offers a healthy working and learning environment. Additionally, it enhances output and product quality across a range of job functions[4], e.g., safe, and appealing bicycle paths[5].

All these functions make the green infrastructure environmentally, vitally, socially, and economically essential inside and outside urbanization[6].

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[1] U.S. EPA, 2023, *Benefits of Green Infrastructure*
[2] Lau, 2018, *Stacking Green Infrastructure Benefits: A Spatial Multi-Criteria Approach to Green Infrastructure Planning in Seattle, Washington.*, p. 9
[3] Neveen Youssef Azmy, 2020, البنية التحتية الخضراء وتأثيرها على العمران, p. 69
[4] Ibid.
[5] Hansen et al., 2017, *Urban Green Infrastructure Planning: A Guide for Practitioners*, p. 27
[6] Neveen Youssef Azmy, 2020, البنية التحتية الخضراء وتأثيرها على العمران, p. 5

Table 3-9 Green Infrastructure Functions and Benefits.

Green Infrastructure Functions	
Environmental And Natural Functions	Temperature regulation
	Carbon Sequestration
	Reduced Air Pollution and Greenhouse Gas Emissions.
	Reduced Energy Use.
	Reduces Urban Heat Island.
	Increase thermal comfort of the buildings
	Noise absorption
	Soil stabilization
	Enhanced Stormwater Management and Water Quality.
Biological and vital functions	Enhance species resilience
	Wood and food production
	Biofuel production
Economic functions	Increases property values
	Investing in green infrastructure
	Food production.
	Reduce heating and cooling costs
Social and humanitarian functions	Improved Human Health and Comfort.
	Enhancing the aesthetic appearance of the building.
	Enhancing the working and learning environments
	Enhanced Quality of Life.

3.6. Green Infrastructure Practices

Green infrastructure techniques are used to create circumstances that facilitate access to ecological and hydrological processes before urbanization. These techniques are intended to create a sustainable city through an ecology-based approach[1].

[1] Temizel et al., 2021, *Planning, Design And Management In Landscape Architecture*, p. 127

3.6.1. Green Roofs and Walls

a. Green roof:

A green roof is a rooftop that is partially or entirely covered with a growing medium and vegetation planted over a waterproofing membrane[1]. Green roofs offer shade, evapotranspiration, and lower temperatures, suitable for various buildings like industrial, educational, government, offices, commercial properties, and residences, reducing ambient air temperatures[2] (Section 2.7.2 Green Roofs, pp. 28-39).

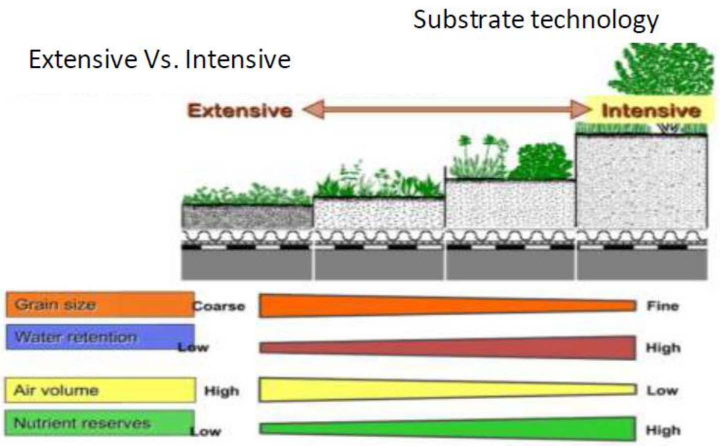
Fig. 3-6 Green Roof. (Source: https://www.urbanscape-architecture.com/do-you-really-know-all-the-benefits-of-green-roofs/,accessed 11/1/2025)

A Comparison of advantages and disadvantages between the two types of green roofs; extensive and intensive green roofs shown in Table 3-10.

[1] U.S. EPA, 2010, *The Value of Green Infrastructure: A Guide to Recognizing Its Economic, Environmental and Social Benefits.*, p. 4

[2] Ryan Bell et al., 2008, *Reducing Urban Heat Islands: Compendium of Strategies - Green roofs*, p. 1

Table 3-10 Comparison between extensive and intensive green roofs. (Source: Baniya et al. (2018), p. 146.)

	Extensive green roof	*Intensive green roofs*
		
Characteristic	- Thin growing medium. - Little or no irrigation. - Stressful conditions for plants. - Low plant diversity. - Slopes up to 30° & higher. - Less expensive	- Deep soil. - Irrigation system. - More favorable condition of plants. - High plant diversity. - Relatively flat - More expensive
Advantage	- Lightweight: The roof generally does not require reinforcement. - Suitable for large areas. - Low maintenance and long life. - No need for irrigation and specialized drainage systems. - Less technical skill needed. - Often suitable for retrofit projects. - vegetation grows spontaneously. - Relatively inexpensive. - Looks more natural. - Easier for planning authority to demand as a condition of planning approval.	- Greater diversity of plants and habitats. - Good insulation properties. - Simulate a wildlife garden on the ground. - Can be made attractive visually. - Can be utilized for various purposes i.e., recreation and food cultivation as open spaces. - More energy efficiency and stormwater retention capacity. - Longer membrane life.
Disadvantage	- Less energy efficiency and stormwater retention benefits. - Limited choice of plants. - Less use for recreation or other uses. - Unattractive, especially in winter.	- Greater weight loading on the roof. - Need for irrigation and drainage systems, requiring energy, water, and materials. - Higher finance and maintenance costs. - More complex systems and skills.

b. Green walls:

Green walls (Fig. 3-7), also known as living walls or vertical gardens, are structures that allow vines to grow on exterior walls, or they can be more detailed with plants attached to the wall[1].

Fig. 3-7 Musée du Quai Branly in Paris. (Source: https://architizer.com/blog/product-guides/product-guide/eantka-green-walls/, accessed on 27/12/2024)

Green walls can also be classified into two groups based on their construction characteristics[2]:

- Green facades involve plants that climb or cascade along building walls, growing vertically either upward or downward.
- A Living Wall System (LWS) is a cutting-edge cladding approach that incorporates greenery into architectural design. These systems allow a variety of plant species to grow vertically, covering significant portions of high-rise building surfaces. Table 3-11 shows green roofs and walls benefits.

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[1] Ibid.p. 5
[2] Omrany, GhaffarianHoseini, GhaffarianHoseini, Raahemifar, & Tookey, 2016, *Application of passive wall systems for improving the energy effciency in buildings: A comprehensive review*, p. 1261

Table 3-11 Green roof and walls Benefits Checklist.

Green Roof Functions		***check***
Environmental And Natural Functions	Temperature regulation	✓
	Carbon Sequestration	✓
	Reduced Air Pollution and Greenhouse Gas Emissions.	✓
	Reduced Energy Use.	✓
	Reduces Urban Heat Island.	✓
	Increase thermal comfort of the buildings	✓
	Noise absorption	✓
	Soil stabilization	
	Enhanced Stormwater Management and Water Quality.	✓
Biological and vital functions	Enhance species resilience	✓
	Wood and food production	✓
	Biofuel production	
Economic functions	Increases property values	✓
	Investing in green infrastructure	
	Food production.	✓
	Reduce heating and cooling costs	✓
Social and humanitarian functions	Improved Human Health and Comfort.	✓
	Enhancing the aesthetic appearance of the building.	✓
	Enhancing the working and learning environments	✓
	Enhanced Quality of Life.	✓

3.6.2. Tree Planting

Tree planting provides numerous ecological, economic, and social benefits, whether measured on a tree-by-tree or large-scale urban forest scale[1]. (Section 2.7.12.7.1 Green Coverage, pp. 24-28). Table 3-12 shows tree planting benefits.

Table 3-12 Tree Planting Benefits Checklist.

Tree Planting Functions		***check***
Environmental And Natural Functions	Temperature regulation	✓
	Carbon Sequestration	✓
	Reduced Air Pollution and Greenhouse Gas Emissions.	✓
	Reduced Energy Use.	✓
	Reduces Urban Heat Island.	✓
	Increase the thermal comfort of the buildings.	
	Noise absorption	✓
	Soil stabilization	✓
	Enhanced Stormwater Management and Water Quality.	✓
Biological and vital functions	Enhance species resilience	✓
	Wood and food production	✓

[1] U.S. EPA, 2010, *The Value of Green Infrastructure: A Guide to Recognizing Its Economic, Environmental and Social Benefits.*, p. 6

Tree Planting Functions		check
	Biofuel production	✓
Economic functions	Increases property values	✓
	Investing in green infrastructure (Increased Pavement Life)	✓
	Food production.	✓
	Reduce heating and cooling costs.	✓
Social and humanitarian functions	Improved Human Health and Comfort.	✓
	Enhancing the aesthetic appearance of the building.	✓
	Enhancing the working and learning environments	✓
	Enhanced Quality of Life.	✓

3.6.3. Bioretention and Infiltration Practices

Bioretention and infiltration practices include rain gardens, bioswales, and wetlands (Fig. 3-8). Rain gardens are best planted with native grasses to collect water from roof downspouts and impervious surfaces. Installing bioswales near paved areas allows water to pool and drain, trapping silt and pollutants[1]. Table 3-13 shows bioretention and infiltration benefits.

Fig. 3-8 Bioswale on the side of the road (left) (Source (left): Braquinho et al., p. 19), *Rain Garden (right)* (Source (right): Temizel et al. (2021), p. 128)

Table 3-13 Bioretention and Infiltration Benefits Checklist.

Bioretention and Infiltration Functions		check
Environmental And Natural Functions	Temperature regulation	✓
	Carbon Sequestration	✓
	Reduced Air Pollution and Greenhouse Gas Emissions.	✓
	Reduced Energy Use.	
	Reduces Urban Heat Island.	✓
	Increase thermal comfort of the buildings.	
	Noise absorption	
	Soil stabilization	
	Enhanced Stormwater Management and Water Quality.	✓

[1] Ibid.p. 8

Bioretention and Infiltration Functions		*check*
Biological and vital functions	Enhance species resilience	✓
	Wood and food production	
	Biofuel production	
Economic functions	Increases property values	
	Investing in green infrastructure	✓
	Food production.	
	Reduce heating and cooling costs	
Social and humanitarian functions	Improved Human Health and Comfort.	✓
	Enhancing the aesthetic appearance of the building.	✓
	Enhancing the working and learning environments	
	Enhanced Quality of Life.	✓

3.6.4. Permeable Pavements

Permeable pavement like pervious concrete, porous asphalt, and interlocking permeable pavers (Fig. 3-9), facilitates the absorption and infiltration of rainwater and snow melt on-site[1].Table 3-14 shows permeable pavements benefits.

Fig. 3-9 Interlocking Permeable Paver (left), Concrete Grass Permeable Pavement Parking (right) (Source: U.S. EPA (2010), p.9,38).

Table 3-14 Permeable Pavements Benefits checklist.

Permeable Pavements Functions		*check*
Environmental And Natural Functions	Temperature regulation	✓
	Carbon Sequestration	
	Reduced Air Pollution and Greenhouse Gas Emissions.	✓
	Reduced Energy Use.	✓
	Reduces Urban Heat Island.	✓
	Increase thermal comfort of the buildings	
	Noise absorption	
	Soil stabilization	

[1] Ibid.p. 10

Permeable Pavements Functions		check
	Enhanced Stormwater Management and Water Quality.	✓
Biological and vital functions	Enhance species resilience	
	Wood and food production	
	Biofuel production	
Economic functions	Increases property values	
	Investing in green infrastructure (Increased Pavement Life)	✓
	Food production.	
	Reduce heating and cooling costs	
Social and humanitarian functions	Improved Human Health and Comfort.	✓
	Enhancing the aesthetic appearance of the building.	
	Enhancing the working and learning environments	
	Enhanced Quality of Life.	✓

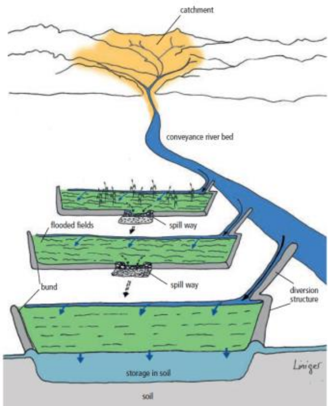
3.6.5. Water Harvesting

Water harvesting is the use of rainwater for irrigation and toilet flushing as a resource[1]. Water harvesting technologies are categorized based on factors like agro-climatic zone, hydro-climatic hazards, spatial scale, size, catchment type, storage systems, geographical area, source of water, water use, or origin[2] (Table 3-15).

Table 3-15 Classification of floodwater harvesting based on catchment type. (Source: Cruz (2013), p. 9).

Floodwater harvesting

Flood recession farming, Inland valleys, Floodwater diversion, off-streambed:
– spate irrigation. – floodwater spreading bunds.

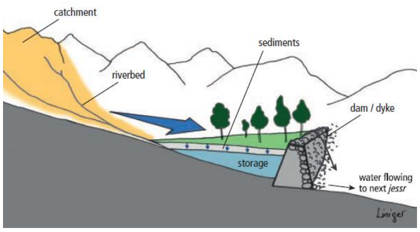


Spate irrigation

Floodwater intake, gate and irrigation canal, Turkana, Kenya.

Floodwater harvesting within stream bed:
– riverbed/wadi and gully reclamation: e.g., jess our, tabias, "warping" dams.
– permeable rock dams.

[1] Ibid.p. 12
[2] Cruz, 2013, *Water Harvesting Proposals*, p. 7



Riverbed reclamation


Warping Dam, Rajasthan, India.

1. Macro catchment WH

Water storage in soil:
– hillside runoff/conduit.
– foothill reclamation: e.g., Limans.
– large semi-circular or trapezoidal bunds.
– road runoff.
– gully plugging / productive gullies.
– cut-off drains (redirection of water).

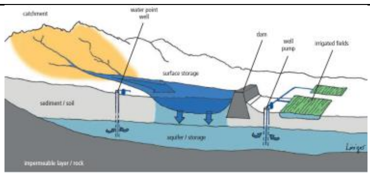
Water storage facilities:

- Surface storage:

– natural depressions.
– ponds and pans.
– excavated ponds.
– cultivated reservoirs/tanks.
– ponds for groundwater recharge.
– surface dams: small earth and stone dams, check dams, rock catchment masonry dams.

- Subsurface storage:

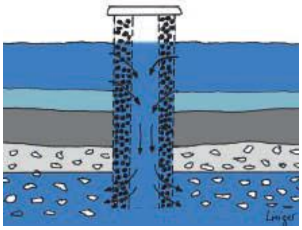
– subsurface, percolation and sand dams.
– subsurface reservoirs: cisterns.



Macro catchment systems


Surface dam, Mongolia.

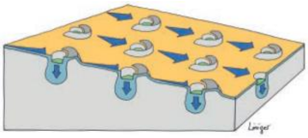
Traditional wells:
– horizontal wells. – recharge/injection wells.


Recharge/injection well

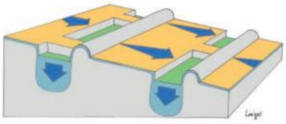

Kanda Rock catchment, Afghanistan.

2. Micro catchment WH

Pits and basins:
– small planting pits.
– micro-basins: e.g., small semi-circular bunds, eyebrow terraces, mechanized Vallerand basins;



Planting pits

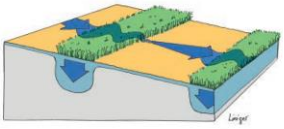


Semi-circular bunds

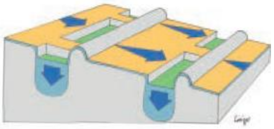
Micro catchment with cemented surface, Loess Plateau, China.

Cross-slope barriers:

– vegetative strips.
– contour bunds and ridges.
– tied ridges.
– stone lines and bunds.
– contour bench terraces (e.g., fanya juu).



Vegetative strips

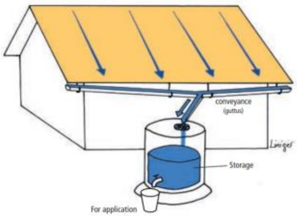


Contour lines and trenches

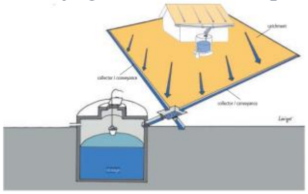
Planting pits for afforestation, Loess Plateau, China.

3. Rooftop & Courtyard WH

Catchment:
Roofs, Courtyards:
– including surfaces of rock, compacted earth, and sealed or paved surfaces.
– plastic sheets, corrugated iron sheeting.
Storage:
– tanks. – reservoirs. – cisterns.



Rooftop Water Harvesting



Courtyard WH combined with rooftop WH

Rooftop and underground tank of a local church, Kenya.

The benefits of water harvesting are shown in Table 3-16.

Table 3-16 Water Harvesting Benefits Checklist.

Permeable Pavements Functions		***check***
Environmental And Natural Functions	Temperature regulation	✓
	Carbon Sequestration	
	Reduced Air Pollution and Greenhouse Gas Emissions.	✓
	Reduced Energy Use.	✓
	Reduces Urban Heat Island.	✓
	Increase the thermal comfort of the buildings.	
	Noise absorption	
	Soil stabilization	
	Enhanced Stormwater Management and Water Quality.	✓
Biological and vital functions	Enhance species resilience	
	Wood and food production	
	Biofuel production	
Economic functions	Increases property values	
	Investing in green infrastructure	
	Food production	✓
	Reduce heating and cooling costs	
Social and humanitarian functions	Improved Human Health and Comfort	
	Enhancing the aesthetic appearance of the building	
	Enhancing the working and learning environments	
	Enhanced Quality of Life.	

3.7. Conclusion

Green infrastructure (GI) offers a sustainable and effective impact on Urban Heat Island (UHI) mitigation and climate change adaption, by incorporating natural cooling mechanisms such as shading, evapotranspiration, and enhanced airflow, green infrastructure improves thermal comfort in densely populated areas. GI practices not only reduce heat buildup, energy consumption, air pollution, greenhouse gas emissions, and air temperature, but they also blend seamlessly into urban landscapes, providing additional ecological and social benefits. GI elements and practices can be classified according to their application in urban areas as shown in Table 3-17.

Table 3-17 GI elements and practices can be classified according to their application in urban areas. (Source: Author)

Position applied		***Elements***
Street green	Street side Squares Walls	- Bioswale. - Tree allays. - Green verge. - Riverbank green. - Railroad bank.
Building	Roofs Walls Gardens	- Green balcony. - Green wall (ground base – façade bound). - Green roof (Extensive – Intensive). - Atrium. - Private garden. - Green playground - Botanical garden/ arboretum.
Parking lot green		- Pocket Park. - Bioswale. - Green verge. - Tree allays.
Public and Recreational area		- Parks. - Neighbourhood and Institutional green space. Cemetery and churchyard. - Green sports Facilities. - Camping areas. - Community spaces. Zoological garden.
Natural and Agricultural areas		
Blue spaces		

As cities continue to expand, adopting green infrastructure principles is essential for creating livable, resilient urban spaces, governments need plans to upgrade and expand their green infrastructure, Table 3-18 shows the methods to achieve green infrastructure principles in cities urban spaces.

Table 3-18 Methods to Achieve Green Infrastructure Principles in Cities. (Source: Author)

GI Principles	***Methods***	
Integration of green and grey infrastructure	linking green spaces with (transport – stormwater) infrastructure and buildings	
	Tree planting in streets and car parking	
	Blue infrastructure complete grey infrastructure	
Connectivity	Natural and semi-natural spaces	
	Green roofs	
	Parks	
	Blue spaces	
	Green corridors	
	Agriculture lands	
Multifunctionality	Provisioning services	
	Cultural functions	Recreation and mental and physical health
		Education and Science
		Tourism
	Biodiversity functions	
	Regulating services	Ventilation/Wind buffer
		Noise mitigation
		Temperature regulation, Global climate regulation
Social inclusion		

To meet the environmental, social, biological, and economic demands communities need by applying green infrastructure the following could be followed:

- Integrating green spaces with conventional infrastructure, like transportation and stormwater management, can maximize environmental, social, and economic benefits.
- Create green networks to promote biodiversity and ecosystem services. This includes developing green corridors, connecting parks, and improving blue spaces (such as rivers and canals).
- Address various urban challenges such as climate regulation, recreation, and habitat conservation by enhancing urban green spaces.
- Encourage social cohesion in planning and making decisions that consider stakeholders' needs and ensure equitable access to green space benefits.
- Enhance green infrastructure projects by collaborating across fields, including ecology, urban planning, and architecture.

Green infrastructure practices aim to improve access to ecological and hydrological processes in order to build a sustainable city using an ecology-based approach it could be divided into building scale and urban scale as shown in Fig. 3-10.

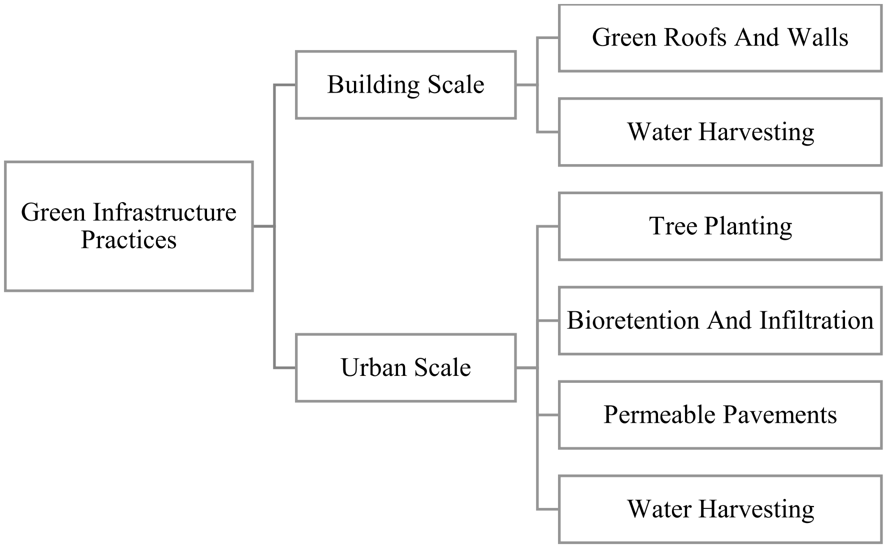


Fig. 3-10 Green infrastructure practices. (Source: Author)

To evaluate the effectiveness of green infrastructure, the following chapter will examine six cities in the same climate zone that all apply green infrastructure elements into their urban design, analyzing GI elements and principles in each city and assessing their impact on land surface temperature (LST). These studies will provide a further understanding of how green infrastructure helps to reduce UHI phenomena.

CHAPTER 4

ANALYTICAL STUDIES

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4.1. Introduction

Green infrastructure (GI) is essential for creating sustainable, resilient, and healthy urban and natural environments. As one of UHI mitigation strategies, this chapter analyzes the green infrastructure elements and principles in different existing urban districts that used green infrastructure (GI) in their urban design and share the same climate zone and urban properties, to evaluate its effectiveness on land surface temperature using GIS maps, as it directly affected the urban heat island phenomenon, The case studies were selected from existing cities due to their ongoing urban and environmental challenges, which make them suitable for examining the effectiveness of green infrastructure in mitigating the Urban Heat Island (UHI) phenomenon. The chapter will discuss GI elements and principles that help in decreasing the LST in each case.

The UHI effect impacts cities in all climate regions, with larger cities experiencing higher magnitudes, particularly in hot arid climates[1].the desert climate or arid climate (in the Köppen climate classification BWh) the Hot-month average temperatures are normally between 29°C and 35°C, and midday readings of 43°C to 46°C are common[2]. The study took place on 12 July 2023, the data was chosen as July and August have the maximum temperature of the year. The study is on three local districts and three international ones, the areas were chosen due to the existence of GI in their urban areas as well as the existence in the same climatic zone The local districts are located in Egypt; Maadi district – Zamalek Island and Heliopolis district, while the international districts are in Baghdad, Iraq – Dubai, UAE and Encanto Village, Phoenix, AZ, USA (Fig. 4-1).

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[1] Hedquist & Brazel, 2014, *Seasonal variability of temperatures and outdoor human comfort inPhoenix, Arizona, U.S.A.*, p. 377

[2] “Hot desert climate (BWh),” n.d.

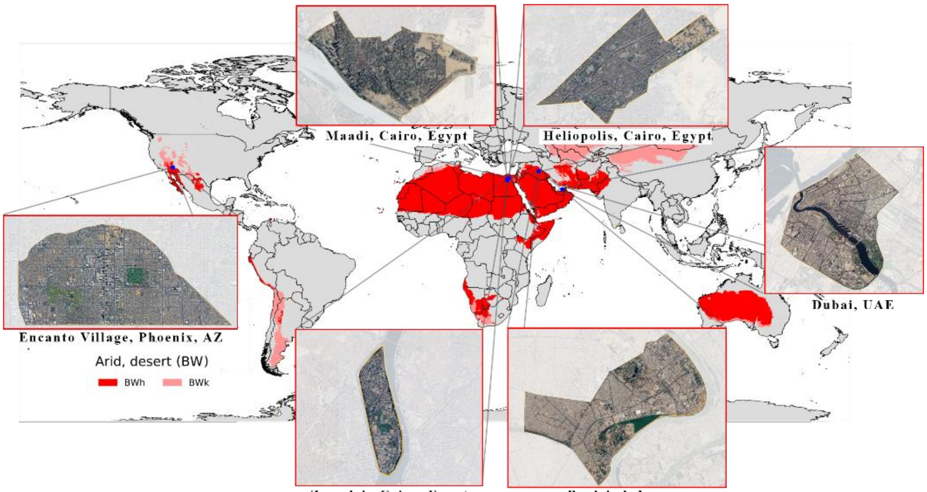

Fig. 4-1 Case Study Locations According to Dry Hot Climate Areas. (Source: https://skybrary.aero/articles/hot-desert-climate-bwh, Google Earth)

Tools and Methods:

The land surface temperature (LST) and vegetation index were derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Google Earth. The land surface temperature measurements were derived using MODIS/Terra Land Surface Temperature/3-Band Emissivity 8-Day L3 Global 1km SIN Grid (MOD11A2) imagery, while the vegetation index maps were derived using MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid (MOD13Q1) imagery, the image were input in ArcMap 10.7.1 program, part of the ArcGIS software package. All thermal images were on 12 July 2023.

4.2. Local Cases

The chosen cases are in Egypt; Maadi district, Zamalek Island and Heliopolis district this area characterizes by its unique green spaces.

4.2.1. Case 1: Maadi, Cairo, Egypt.

Al Maadi district is located south of the Greater Cairo Urban Region on the east bank of the Nile River, Egypt (Fig. 4-2) (latitude: 29 W56053.3″N; longitude: 31 W15024.6″E)[1]. Al Maadi district was planned as a residential neighborhood of a single format[2], the land use is mainly residential, and the commercial units, small factories and

[1] El-Dars, Abdel Rahman, Salem, & Abdel-Aal, 2015, *Algal control and enhanced removal in drinking waters in Cairo, Egypt*, p. 1062

[2] Bek et al., 2018, *The effect of unplanned growth of urban areas on heat island phenomena*, p. 5

military training areas exist only in designated areas on the district sides[1]. The study area is about 7 square km.

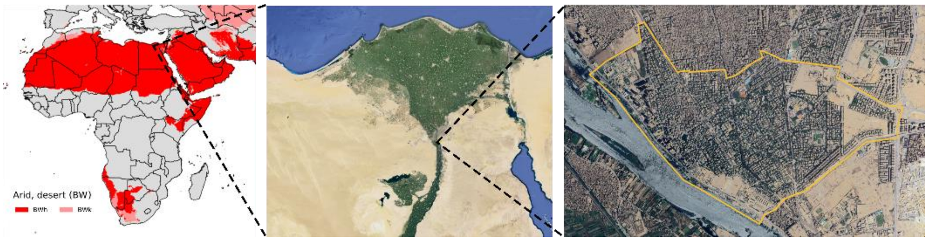

Fig. 4-2 Maadi, Cairo, Egypt. (Study Area). (Source: Google Earth)

a. Maadi Climatic Parameters

The climate of Maadi can be classified as desert climate, where rainfall is scarce and the rainy season is from October to May, where rainfall increases especially from November to February. In the summer, from June to September, there is no precipitation at all and the region is semi-arid, where it is hot and dry, The average annual temperature is 22.1°C. the maximum temperature in most areas is approximately 36.8°C in July and August, averaging 21.8°C. January is the coldest month with rain falls and the lowest temperature can reach 7.8 °C with an average of 13.4°C [2].

b. Maadi Urban Parameters

- **Material properties:** Streets are paved asphalt, and buildings' external finishing materials: are natural stone, exposed brick, artificial stone white, or earth colours (natural external whiteness (beige in its shades/bray in its shades)[3] (Fig. 4-3).
- **Urban geometry:** Streets' widths are more than 10 m and the height of the buildings is about three floors above the ground[4].
- **Urban density:** the manned space: 7 square km. The number of the estimated population until the date 1/7/2021 reaches about 93,291 inhabitants[5].

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[1] Mahmoud & Selman, 2011, *Natural infrastructure concept in arid regions: Two case studies in Egyptian context*, p. 352

[2] "MAADI AL KHAHIRI CLIMATE (EGYPT)," n.d.

[3] 2011, الحدود واشتراتات منطقة المعادي

[4] Bek et al., 2018, *The effect of unplanned growth of urban areas on heat island phenomena*, p. 4

[5] *Central Agency for Public Mobilization and Statistics*, 2021

Fig. 4-3 Maadi Street in Cairo. (Source: https://www.youtube.com/watch?v=fzvsZ2J6oz4 , https://www.youtube.com/watch?v=COItmxeeWLs , accessed: 16/12/2023)

c. Maadi Green Infrastructure Analysis

The district has squares and green spaces as well as afforestation areas in streets, there are private gardens around the buildings (Fig. 4-3), public parks and trees canopy along the Nile corniche (Fig. 4-4). Table 4-1 shows the GI elements distribution in the district.

Fig. 4-4 Maadi Nile corniche.
(Source: left: https://theculturetrip.com/africa/egypt/articles/an-insiders-guide-to-maadi-cairo , right: https://www.youtube.com/watch?v=fzvsZ2J6oz4 , accessed: 16/12/2023)

Table 4-1 Maadi district green infrastructure elements analysis. (Source: Author, Google Earth Street View, https://shorturl.at/l9RyN, accessed 4/7/2024)

Position	***Image***	
Streets - *Squares:* Squares with green areas and vegetation.		
- *Sides:* Tree alleys along the middle and side of streets		
- *Railroad:* Railroad bank verge.		
- *Walls:* Trees are used as fences and on walls.		
- *Riverbank:* Trees have been planted along the riverbank, and cornish is being planted, and some activities are taking place.		
Building: Villas with private gardens.		
Parking lots: Not all parking lots have trees.		

Position	Image	
Public areas: Small parks in squares.		
Sports facilities.		
Blue spaces: The Nile river		
Some villas and schools have their private pool.		
Agricultural area	There is an agricultural area on the other side of the river out of the study area.	
Natural area: Shrubs are grown in abundant areas on the side of the district.		

- **Integration of green and grey infrastructure:** The district features a successful integration of elements where; tree alleys in streets and parking lots, recreational and environmental spaces with a historic blue way, as well as all houses built as villas or palaces with private gardens and horticulture lands[1].
- **Connectivity:** Maadi district showcases a successful green network of elements, connecting the Nile riverbank and transport with pedestrians' green corridor. Tree-lined streets for cars and

[1] Mahmoud & Selman, 2011, *Natural infrastructure concept in arid regions: Two case studies in Egyptian context*, p. 353

pedestrians, with green node squares, are designed according to radial axes. Open green spaces are common in social clubs and the Maadi Sports Centre[1] (Fig. 4-5).

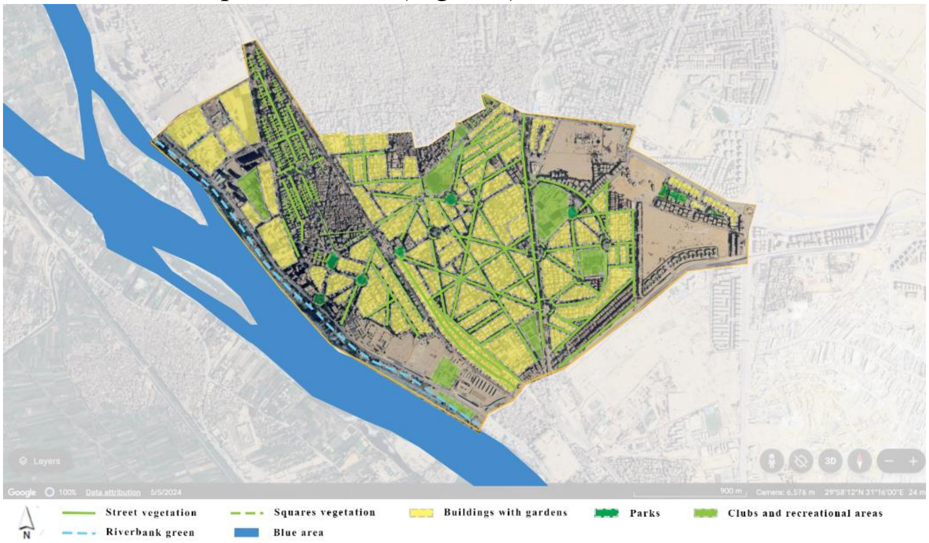

Fig. 4-5 Maadi Green Infrastructure Connectivity Analysis. (Source: Author, based on Google Maps)

- **Multifunctionality:** The presence of the Nile River in the area provides urban character and recreational value, attracting tourists to the district's various recreational and environmental spaces, while private gardens and urban spaces provide noise reduction and climate regulation[2].
- **Social inclusion:** Environmental awareness enhances social values and fosters cooperation between individuals, non-governmental organizations, and governmental organizations[3].

d. Maadi Urban Heat Island Analysis

The land surface temperature (LST) of the Maadi area (Fig. 4-6 a, b) and the vegetation index (Fig. 4-6 c), during the summer shows that the temperature in the surrounding areas of Maadi district is 36˚C to 38˚C during the day and about 28˚C during the night. while Maadi urban area is 35˚C to 36˚C during the day and 27.7˚C to 27.9˚C during the night, With 2-3 degrees lower than the surrounding areas during the day and about 0.5˚C during the night. The area near the river has the lower LST.

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[1] Ibid.
[2] Ibid.
[3] Ibid.p. 355

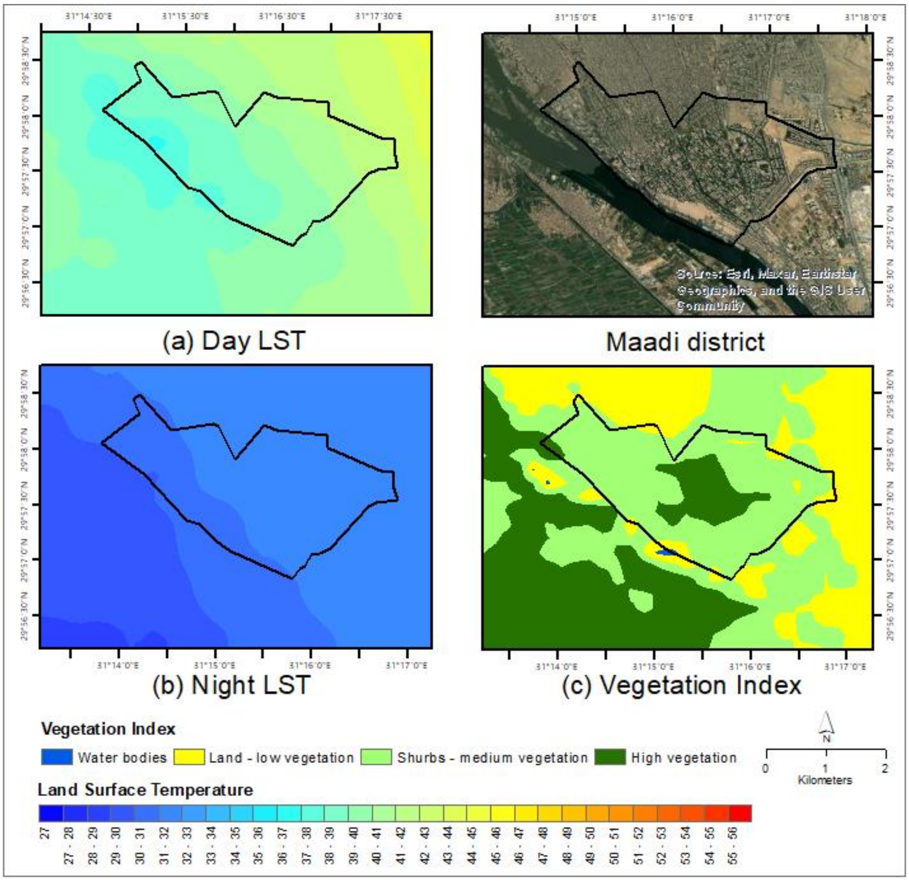

Fig. 4-6 (a) Day LST, (b) Night LST and (c) vegetation index thermal map for Maadi area and surrounding area on 12 July 2023. (Source: https://ladsweb.modaps.eosdis.nasa.gov/ *,accessed: 2/6/2024*)

From Fig. 4-6 it has been observed that the agricultural land has the lowest LST at day and night as well as the areas near the riverbank, the temperature increase as the vegetation decrease.

4.2.2. Case 2: Zamalek, Cairo, Egypt

Zamalek island is located south of the Greater Cairo Urban Region on the Nile River, Egypt (Fig. 4-7) (latitude: 30°03'42"N; longitude: 31°13'15"E). AL-Zamalek Island, known for its extensive green space and Gezira Sporting Club, serves as a recreational hub in modern Cairo, alongside landmarks like the opera house and Cairo Tower[1]. The study area is about 3 square km.

[1] Ibid.p. 346

Fig. 4-7 Zamalek, Cairo, Egypt. (Study Area). (Source: Google Earth)

a. Zamalek Climatic Parameters

The climate of Cairo can be classified as desert climate, There is virtually no rainfall during the year. The average annual temperature is 22.1°C. the maximum temperature in most areas is approximately 36.8°C in July and August with an average of 29.2°C. January is the coldest month with rain falls and the lowest temperature can reach 7.8°C with an average of 13.4°C [1].

b. Zamalek Urban Parameters

- **Material properties:** The streets are paved asphalt, and the buildings' external finishing materials: are artificial stone white, or earth colours (beige in its shades/bray in its shades)[2].
- **Urban geometry:** The maximum height allowed is equivalent to the street's width, with a maximum of 19 meters[3], about 4 floors from the ground.
- **Urban density:** the manned space: 3 square km. The number of the estimated population until the date 1/7/2021 reaches about 15,742 inhabitants[4].

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[1] "Cairo climate and weather," n.d.
[2] حدود وأسس الحفاظ على جزيرة الزمالك ذات القيمة المتميزة, 2022, p. 8
[3] Ibid.
[4] *Central Agency for Public Mobilization and Statistics*, 2021

Fig. 4-8 Zamalek Streets Footage. (Source: https://timesofegypt.com/2020/07/59009/, https://www.youtube.com/watch?v=j2MhD7sCkD4, https://www.youtube.com/watch?v=n3Bv5JmGsYQ, accessed: 31/5/2024)

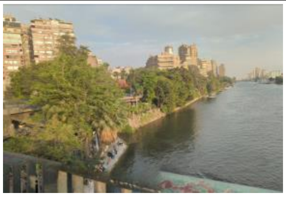
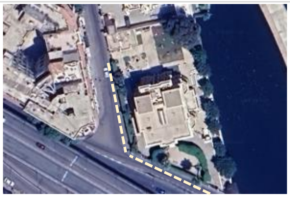
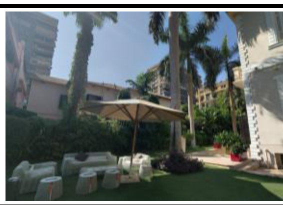
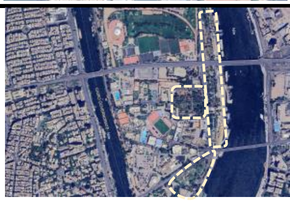
c. Zamalek Green Infrastructure Analysis

El-Zamalek Island is characterised by public green spaces and hotels besides the Gezira Club, the most extensive green space designed & established in modern Cairo, alongside other prestigious landmarks[1], Table 4-2 shows the GI elements distribution in the district.

Fig. 4-9 Recreational functions in AL-Zamalek Island and its banks. Left: green spaces in Gezira sporting club. Right: Opera cultural Centre and the public Nile Park. (Source: Abdou, Abd El Gawad, & Tarek Fouad, 2016, p. 9)

[1] Abdou, Abd Elgawad, & Tarek Fouad, 2016, *GREEN INFRASTRUCTURE TO ACHIEVE SUSTAINABILITY IN URBAN DESIGN Nile Corridor in Great Cairo as a Case Study*, p. 9

Table 4-2 Zamalek green infrastructure elements analysis. (Source: Author, Google Earth Street View photo, https://shorturl.at/OOmje, accessed 4/7/2024)

Position	***Images***	
Streets - *Squares:* There is one square in the study area with green vegies.		
- *Sides:* Tree canopies are on the street's sides.		
- *Riverbank:* Trees and plants on the riverbank as well as some activities.		
- *Walls:* Green walls and plants on the building fences.		
Building: Some buildings have private gardens.		
Parking lots: The parking in streets shaded with tree canopies while the large parking areas have less vegetation.		
Public areas: Public parks are located in the southern part of the island.		

Position	Images	
The island is characterized by its clubs and recreational areas in the south area of the island.		
Blue spaces: Nile River around the island.		
Natural and semi-natural areas: There are some old and natural trees in the area as well as Aquarium Grotto Garden.		

- **Integration of green and grey infrastructure:** The area features a successful integration of elements where; tree alleys on the street sides and parking lots, recreational and environmental spaces with the Nile River[1].
- **Connectivity:** the area has a successful GI network beginning with the trees allay on the street side to the green parks and the recreational areas with the river green banks (Fig. 4-10).

Fig. 4-10 Zamalek Green Infrastructure Connectivity Analysis. (Source: Author, based on Google Maps)

[1] Mahmoud & Selman, 2011, *Natural infrastructure concept in arid regions: Two case studies in Egyptian context*, p. 353

- **Multifunctionality:** The Nile River serves as a natural social and economic link, connecting islands, urban districts, and greenways, promoting habitats, biodiversity, and hydrology[1].
- **Social inclusion:** The Supreme Council for Urban Planning special purchases for urban coordination and construction on green areas, in addition to construction rates for clubs and parks[2].

d. Zamalek Urban heat island Analysis

land surface temperature (LST) of the Zamalek area (Fig. 4-11 a, b) and the vegetation index (Fig. 4-11 c), during the summer shows that the temperature in the urban areas of Zamalek is 38.4˚C to 40.5˚C during the day and about 29.9˚C to 31.2˚C during the night. while the low vegetation surrounding urban area is 40.6˚C to 42.3˚C during the day and 31.1˚C to 31.5˚C during the night, this shows that the area's temperature is about 2 degrees lower than the low vegetation areas during the day and about 0.5˚C during the night.

[1] Ibid.p. 343
[2] 2022, حدود وأسس الحفاظ على جزيرة الزمالك ذات القيمة المتميزة, p. 5

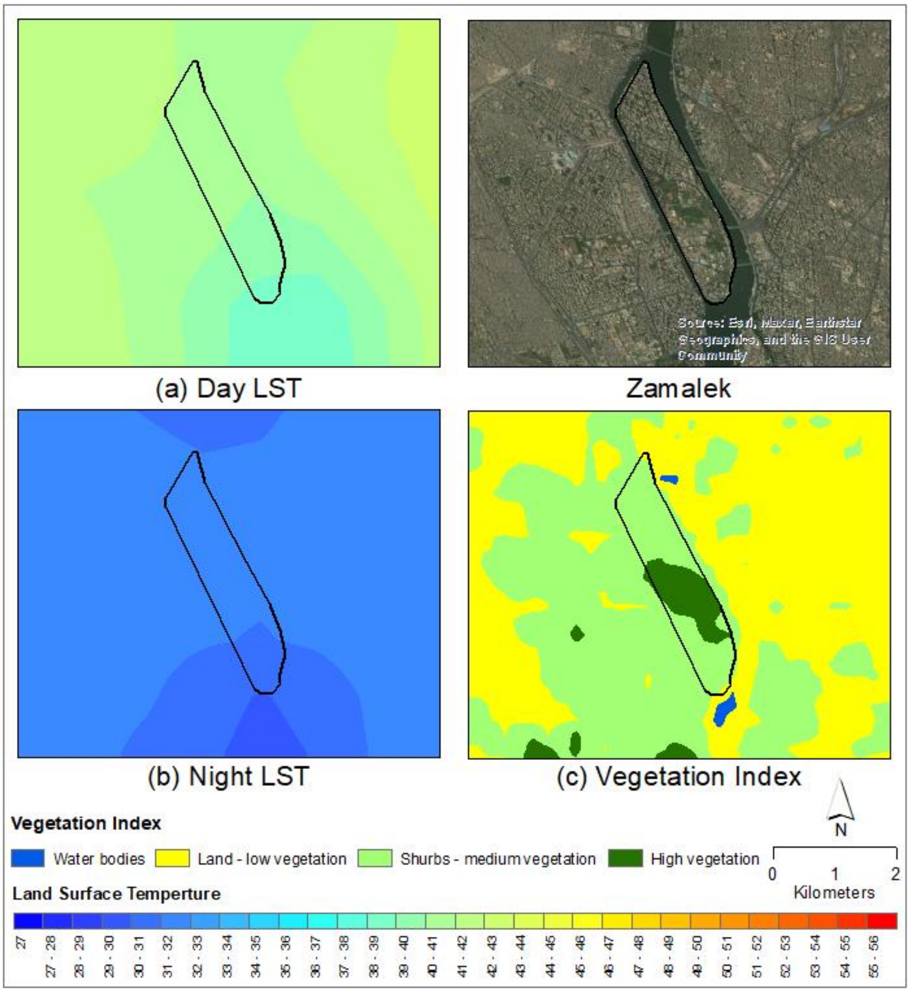


Fig. 4-11 (a) Day LST, (b) Night LST and (c) vegetation index thermal map for Zamalek and surrounding area on 12 July 2023. (Source: https://ladsweb.modaps.eosdis.nasa.gov/ *,accessed: 2/6/2024*)

In Fig. 4-11, it was observed that parks and club part have lower LST, the LST in the island nearly the same.

4.2.3. Case 3: Heliopolis, Cairo, Egypt

Heliopolis is located in the Eastern part of Cairo, Egypt (Fig. 4-12) (latitude: 30°05'58"N; longitude: 31°19'58"E). Heliopolis district is known for its open green spaces in the urban residential district[1], Heliopolis district faces traffic congestion, prompting the construction

[1] Elbardisy, Salheen, & Fahmy, 2021, *Solar irradiance reduction using optimized green infrastructure in arid hot regions: A case study in el-nozha district, cairo, egypt*, p. 4

of 10 flyovers and widening of streets to address urban issues and improve urban morphology[1]. The study area is about 11 square km.

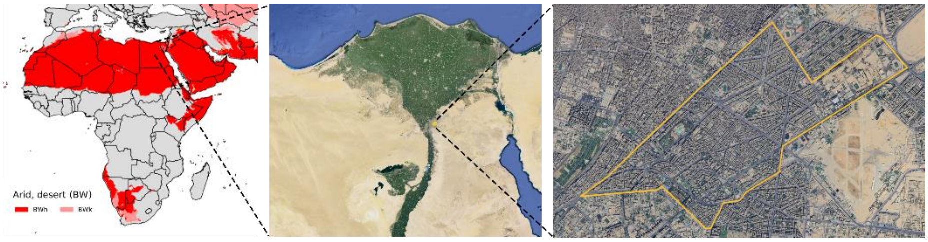


Fig. 4-12 Heliopolis, Cairo, Egypt. (Study Area). (Source: Google Earth)

a. Heliopolis Climatic Parameters

The climate of Cairo can be classified as desert climate, There is virtually no rainfall during the year. The average annual temperature is 22.1°C. the maximum temperature in most areas is approximately 36.8°C in July and August with an average of 29.2°C. January is the coldest month with rain falls and the lowest temperature can reach 7.8°C with an average of 13.4°C [2].

b. Heliopolis Urban Parameters

- **Material properties:** The streets are paved asphalt, and the buildings' external finishing materials: are artificial stone white, or earth colours (beige in its shades/bray in its shades)[3].
- **Urban geometry:** The maximum height allowed is 1.5 equivalent to the street's width, with a maximum of 20-23 meters[4], about 4-5 floors from the ground.
- **Urban density:** the manned space: 11 square km. The estimated population until the date 1/7/2021 reaches about 141237inhabitants[5].

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[1] Hefnawy, 2022, *The Radical Changes in Heliopolis Identity: Towards Urban Green Infrastructure Approach.*, p. 40

[2] "Cairo climate and weather," n.d.

[3] حدود واسس الحفاظ على منطقة مصر الجديدة - ذات القيمة المتميزة, 2022, p. 11

[4] Ibid.p. 12

[5] *Central Agency for Public Mobilization and Statistics*, 2021

Fig. 4-13 Heliopolis Streets Footage.
(Source: https://www.youtube.com/watch?v=_VozHiFar1g , https://www.youtube.com/watch?v=nwj6IPi_3-c, accessed: 11/6/2024)

c. Heliopolis Green Infrastructure Analysis

Heliopolis, known for its unique urban nature with natural features like green open areas and trees, has experienced a dramatic change due to the loss of large green areas and the removal of natural elements. This loss has altered the green identity of the area and raised concerns about futuristic environmental consequences. Despite this, Heliopolis remains one of the highest areas in Egypt with numerous green spaces and recreational areas[1].

[1] Hefnawy, 2022, *The Radical Changes in Heliopolis Identity: Towards Urban Green Infrastructure Approach.*, p. 42

Table 4-3 Heliopolis green infrastructure elements analysis. (Source: Author, Google Earth Street View photo, https://shorturl.at/UeH7A, accessed 4/7/2024)

Position	*Images*
Streets - *Squares:* Many squares had been bridges to avoid the traffic, there are a few green squares.	 
- *Sides:* There is trees and vegetation on the street sides and the middle of the street.	 
- *Walls:* The first green spaces have been planted on the El Mahkama Square bridge.	 
Building: Some buildings have private gardens.	 
Parking lots: Street parking has trees shading, while some parking lots have no vegetation.	 
Public areas: There is a wide park on the western side of the district besides small parks distributed in the district and squares.	 
Sporting clubs and recreational areas distributed in the district.	 
Natural area:	The area has trees 100 years old in the streets and parks.

- **Integration of green and grey infrastructure:** Hundreds of trees are removed and replaced with concrete bridge columns to improve traffic flow in the area, resulting in a loss of green infrastructure integration with grey infrastructure[1]. The state considered planting the bridges' walls and facades to preserve the environment while also beautifying their concrete character[2].
- **Connectivity:** Egypt's plan to widen streets and build a new bridge has led to a decrease in green areas in the district. In 2020, green walls were installed on the sides and columns of the Al-Ahram bridge in Heliopolis, but they cannot replace the lost greenery[3] (Fig. 4-14).

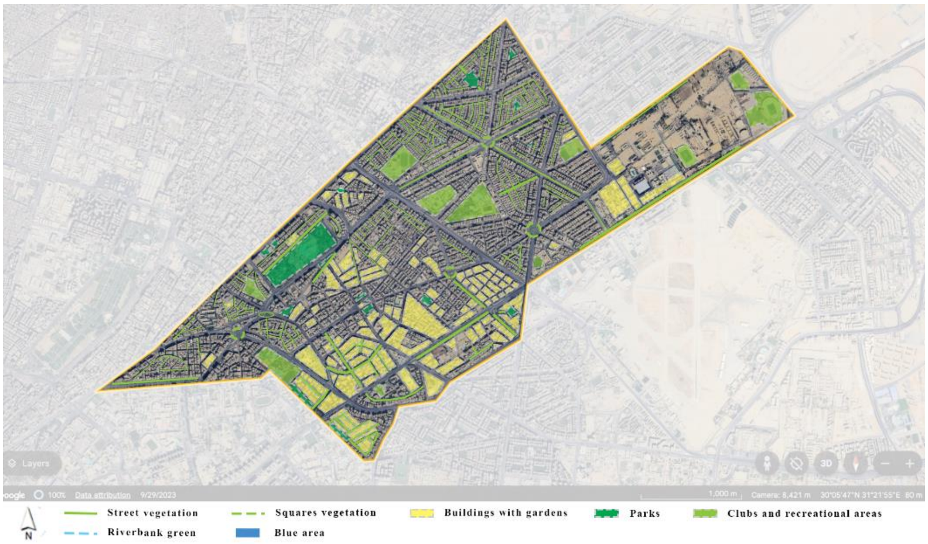

Fig. 4-14 Heliopolis Green Infrastructure Connectivity Analysis.
(Source: Author, based on Google Maps)

- **Multifunctionality:** the trees work as wind puffers, noise regulation for the buildings, and temperature regulation for the presidents.
- **Social inclusion:** The Supreme Council for Urban Planning special purchases for construction rates for clubs and parks[4].

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[1] Nasser, 2020, *Heliopolis development plan... between traffic flow and the loss of the features of the upscale neighborhood*

[2] Azmy, 2023, *Biophilic design as a tool to enhance environmental performance under flyovers.*, p. 11

[3] Aboubakr & Elserafi, 2023, *City Growth Challenges as a Dilemma between Urban Mobility and Livability: A Case Study of Heliopolis*, p. 1806

[4] 2022, حدود واسس الحفاظ على منطقة مصر الجديدة - ذات القيمة المتميزة, p. 7

d. Heliopolis Urban heat island Analysis

The land surface temperature (LST) of Heliopolis (Fig. 4-15 a, b) and the vegetation index (Fig. 4-15 c), during the summer shows that the temperature in the urban areas of Heliopolis is 41.4˚C to 43˚C during the day and about 31˚C to 31.5˚C during the night. while the low vegetation surrounding urban area is 42.5˚C to 43.5˚C during the day and 30.6˚C to 31.6˚C during the night, this shows that the area's temperature is about 0.5-1 degrees lower than the low vegetation areas during the day and about 0.5˚C during the night.

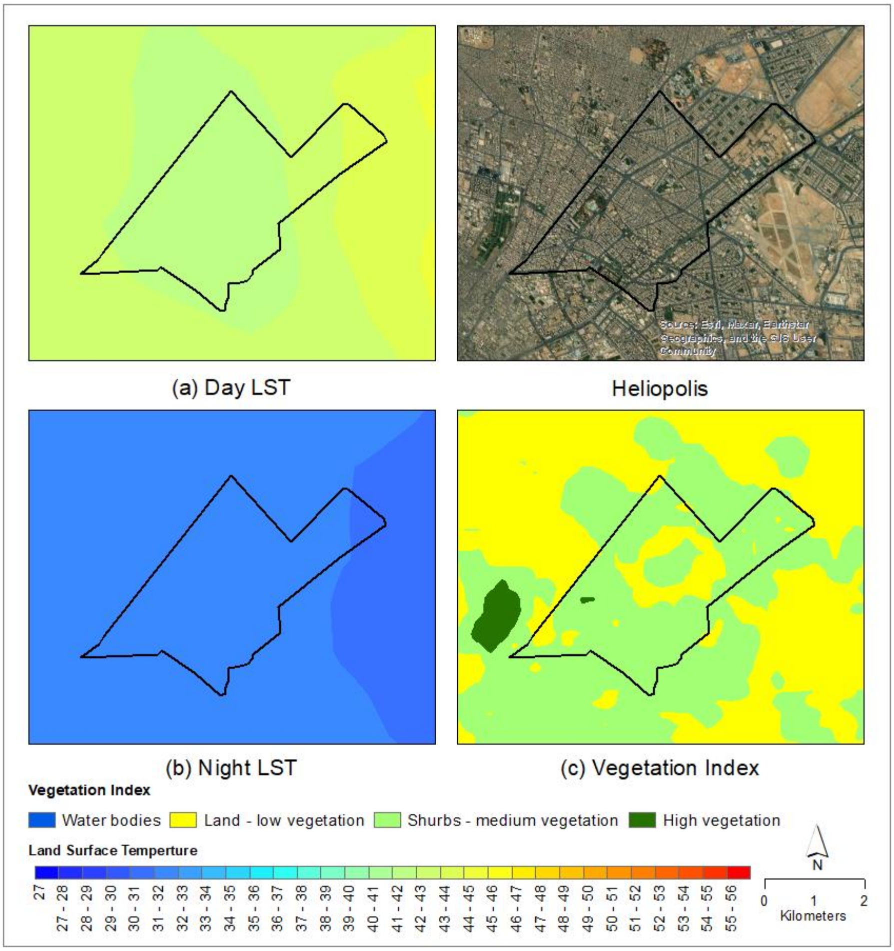

Fig. 4-15 (a) Day LST, (b) Night LST, and (c) vegetation index thermal map for Maadi area and surrounding area on 12 July 2023. (Source: https://ladsweb.modaps.eosdis.nasa.gov/ *,accessed: 2/6/2024*)

It was observed from Fig. 4-15, the LST in the study area during the day and night is nearly the same, during the day as the vegetation decreases (east) the LST increases.

4.3. International cases

The chosen cases are in Baghdad, Dubai, and Phoenix, AZ.

4.3.1. Case 1: Baghdad, Iraq

Baghdad is in the center of Iraq (33°18'42"N latitudes and 44°21'21"E longitudes) and has an area of 894.3 km2. It has the highest population density among Iraqi provinces and ranks second in the Arabian World, after Cairo. The Tigris River divides the city into two halves: Rasafa (Eastern) and Karkh (Western). Baghdad's average elevation above sea level is 34 meters[1]. The area of the present study is located in the center of Baghdad with an area of 25 km^2 (Fig. 4-16).

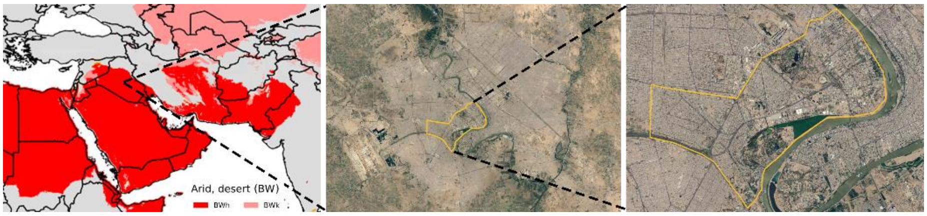

Fig. 4-16 Baghdad, Iraq. (Study Area). (Source: Google Earth)

a. Baghdad Climatic Parameters

The climate of Baghdad can be classified as desert climate, January has the highest relative humidity, whereas June experiences the lowest. The month with the highest precipitation is January, whereas July has the lowest rainfall, The average annual temperature is 25.5°C. the maximum temperature in most areas is approximately 45.3°C in August with an average of 38.6°C. January is the coldest month with rain falls and the lowest temperature can reach 6.1°C with an average of 11.1°C[2].

b. Baghdad (study area) Urban Parameters

- **Material properties:** The streets are paved asphalt, and the buildings' external finishing materials: are natural stone, bricks, blocks and prefabricated Construction[3] (Fig. 4-3).
- **Urban geometry:** Streets' widths are 10 m while the main streets reach up to 40m width, and the height of the buildings is about three floors above the ground and high-rise buildings up to six floors[4].

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[1] Wahab, Naif, & Al-Jiboori, 2022, *Development of Annual Urban Heat Island in Baghdad Under Climate Change*, p. 180

[2] "BAGHDAD CLIMATE (IRAQ)," n.d.

[3] *Number of Buildings in Baghdad Governorate by Envieronment, Type of Building and Type of Outer Walls Construction Material.*, n.d.

[4] "Google Earth," n.d.

- **Urban density:** the urban manned space: 25 square km. The number of estimated population until the date 1/7/2021 reaches about 7,682,136 inhabitants[1].

Fig. 4-17 Baghdad Urban Streets. (Source: Google Maps Photos)

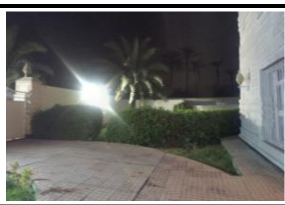
c. Baghdad (study area) Green Infrastructure Analysis:

Baghdad's green areas were not planned to follow the city's size and population, but rather based on random choices or relying on parts of development plans. Baghdad’s green infrastructure consists of public areas, private gardens distributed according to the area of residential plots, and agricultural areas distributed in the city planted as orchards and green belts as Baghdad's comprehensive development plan proposed a green protective belt between urban borders and Mayoralty borders, aiming to create isolation, low intensity building activities, and green open areas[2]. Table 4-4 analyses the GI in the study area.

[1] “تقديرات سكان العراق للفترة (2015-2030) - الجهاز المركزي للاحصاء,” n.d.

[2] Majeed & Abaas, 2023, *An Analysis of Baghdad’s Masterplans Based on the Development of Green Areas*, p. 196

Table 4-4 Case Study Area in Baghdad City Green Infrastructure Elements Analysis. (Source: Author, Google Earth Street View photo, https://shorturl.at/UPFuo, accessed 4/7/2024)

Position	***Images***	
Streets - *Squares:* Green spaces in the middle of the square and on the sides.		
- *Sides:* ▪ Tree canopy in the middle in main streets and street sides.		
▪ The green belt.		
- *Walls:* Planting trees as fences for buildings.		
- *Riverbank green:* Spontaneous plants are grown on the Tigris riverbank beside the Tigris River Cornish.		
Building: Every building has a private garden.		
Parking lots: Trees and green verges in most of the parking lots.		

Position	***Images***	
Public areas: Al-Zawraa park community spaces and zoological garden, as well as small parks in squares.		
Sports clubs and playgrounds.	 	
Blue spaces: Tiges river.		
Bonds in Al-Zawra park		
Agricultural area: Agricultural lands in Um Al-Khanzeer island besides the preservation of orchards and agricultural areas inside the city.		

- **Integration of green and grey infrastructure:** the area features a successful integration of elements where; tree alleys in streets and the green belts in the city, recreational and community spaces in educational and zoological gardens and houses built as villas or palaces with private gardens as well as the presence of agrecultural lands distributed in the city.
- **Connectivity:** the green network is strong near the river banks, the park in the middle of the area makes a good network with the trees on the streets, buildings gardens and the orchards on the rivers (Fig. 4-18).

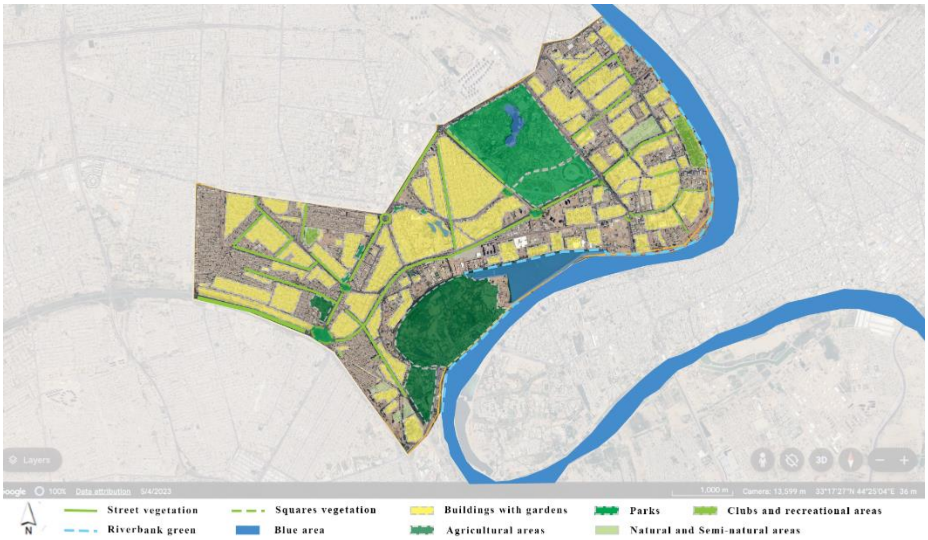


Fig. 4-18 Baghdad Green Infrastructure Connectivity Analysis. (Source: Author, based on Google Maps)

- **Multifunctionality:** The agricultural lands in and around Baghdad are critical to the city's economy, providing crops, improving the climate, and serving as a resource for recreation and entertainment[1].
- **Social inclusion:** Environmental awareness enhances social values and fosters cooperation between individuals, non-governmental organizations, and governmental organizations, The City Development Plan 2030 contained recommendations to improve the environmental and ecological aspects[2].

d. Baghdad (study area) Urban heat island Analysis

The land surface temperature (LST) of the Maadi area (Fig. 4-19 a, b) and the vegetation index (Fig. 4-19 c), during the summer shows that the study area is 46.2˚C to 49.3˚C during the day and 34˚C to 36.5˚C during the night, With 1-2 degrees lower during the day than the very low vegetation areas surrounded and about 1-1.2˚C during the night, the lands near the Tigris River have lower LST due to the sea breeze. The land that is surrounded by water has the lowest LST.

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[1] Ibid.
[2] Ibid.p. 207

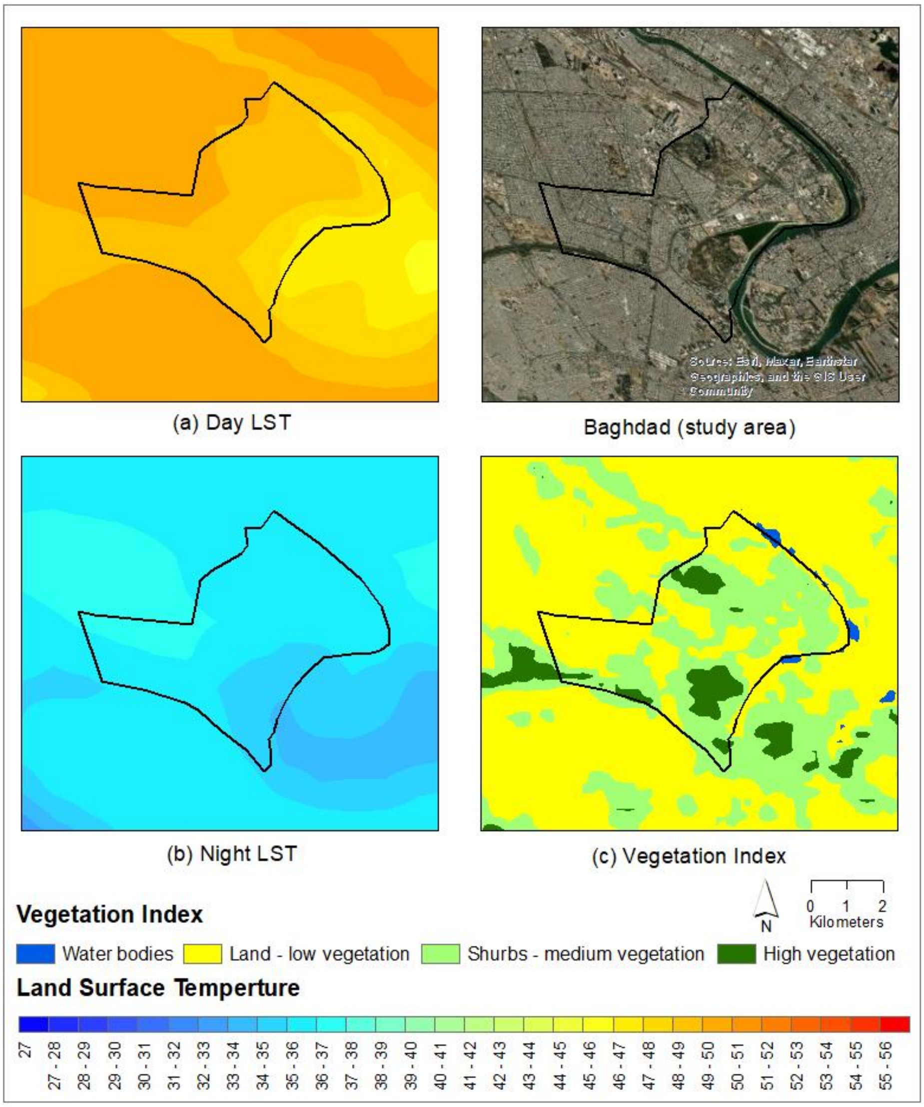


Fig. 4-19 (a) Day LST, (b) Night LST and (c) vegetation index thermal map for the study area in Baghdad 12 July 2023. (Source: https://ladsweb.modaps.eosdis.nasa.gov/ *,accessed: 2/6/2024*)

It was observed from Fig. 4-19 that; The land enclosed by the river has the lowest LST, and the area where the green belt has low LST, the LST increases as the vegetation decreases, the areas with high vegetation have low LST.

4.3.2. Case 2: Dubai, United Arab Emirates

Dubai is among the seven emirates of the United Arab Emirates (UAE). It is located southeast of the Arabian Gulf; the city has a 72-km long coastline on the Arabian Peninsula's eastern shore (latitude: 25°16' N; longitude: 55°18' E)[1]. (Fig. 4-20) Dubai has rapidly urbanized and has become one of the world's most notable urbanizing cities in a noticeably short period. The study area is about 30.5 square km.

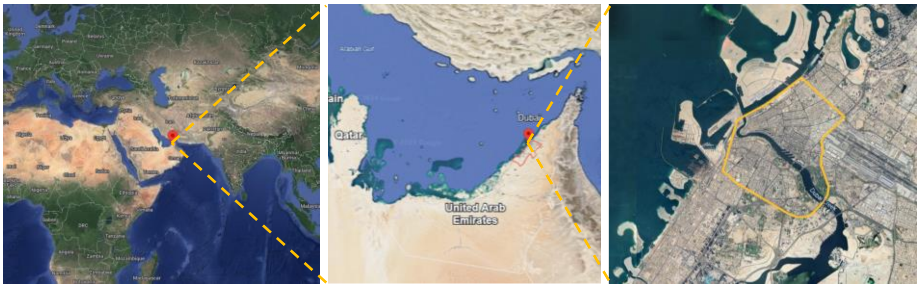


Fig. 4-20 Dubai, United Arab Emirates (Study Area). (Source: google earth)

a. Dubai Climatic Parameters

The climate of Dubai is classified as desert climate (Köppen climate classification: BWh), with virtually no rainfall all year long. The average annual temperature is 28.2°C. it has long, hot summers with soaring temperatures, often exceeding 40°C, and mild, pleasant winters. the maximum temperature in most areas often exceeds 40°C in August with an average of 35.7°C. January is the coldest month with the lowest temperature reaching 14.1°C with an average of 19.4°C[2].

b. Dubai (study area) Urban Parameters

- **Material properties:** The streets are paved asphalt, and the buildings' external finishing materials: are natural stone, artificial stone white, or earth colours (natural external whiteness (beige in its shades/bray in its shades) (Fig. 4-21).
- **Urban geometry:** Streets' width is more than 10 m. The main streets reach 20–40 m. They are straight and paved streets[3], and the height of the buildings differs according to each cluster. Some clysters are about three to five floors above the ground; the buildings on the main streets and Dubai Creek are high-rise towers.

[1] Mohammed, Khan, & Santamouris, 2023, *Numerical evaluation of enhanced green infrastructures for mitigating urban heat in a desert urban setting*, p. 3

[2] "DUBAI CLIMATE (UNITED ARAB EMIRATES)," n.d.

[3] Middel, Lukasczyk, Maciejewski, Demuzere, & Roth, 2018, *Sky View Factor footprints for urban climate modeling*, p. 124

- **Urban density:** the manned space: 30.5 square km. The number of estimated population until 2021 will reach about 475,954 inhabitants[1].

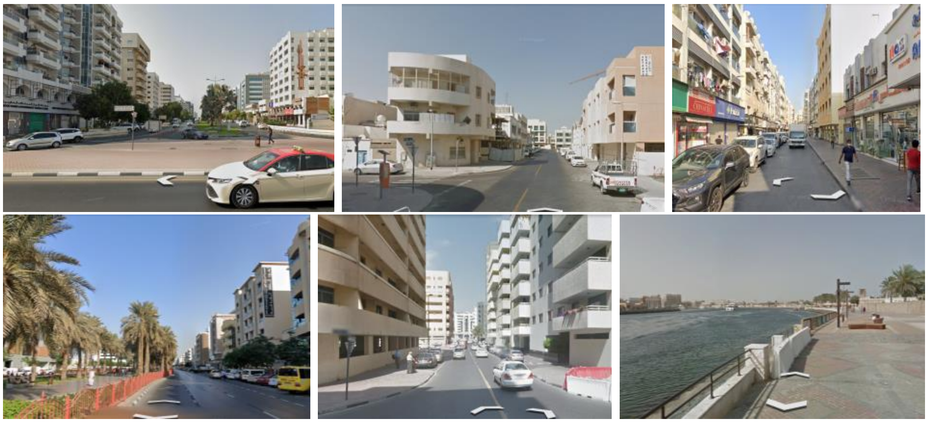
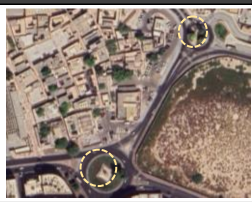
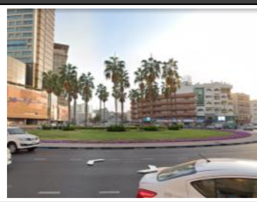


Fig. 4-21 Streets in Dubai. (Source: Google Earth)

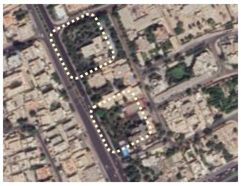
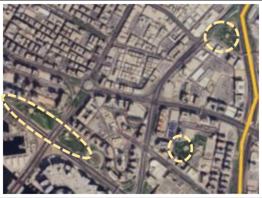
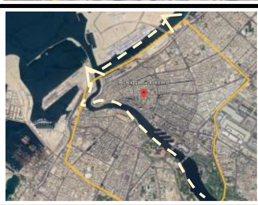
c. Dubai (study area) Green Infrastructure Analysis

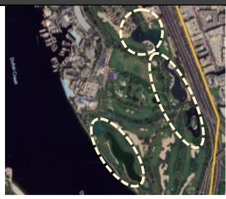
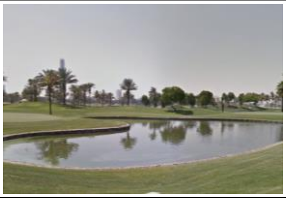
The area is characterized by Dubai Creek with trees and green infrastructure elements in the main streets and residential neighbourhoods (Fig. 4-21), Table 4-5 shows the GI elements distribution in the area.

Table 4-5 Dubai Case Study Area Green Infrastructure Elements Analysis. (Source: Author, Google Earth Street View photo, https://shorturl.at/Rx6iL,accessed 4/7/2024)

Position	*Images*	
Streets - Squares: Squares with green areas on the sides or parks in the middle.		
- Sides: Tree allays along the middle and side of streets.		
- Railroad: The railway is on a bridge with no vegetation.		

[1] *Population Bulletin - Dubai 2021*, 2021

Position	***Images***	
- Walls: Trees are used as fences, not in a wide range.		
Building: Gardens are in high-income clusters of residential buildings.		
Parking lots: Parking lots have no vegetation whereas the ones that do have low vegetation (trees and sidewalk verge).		
Public areas: Parks in the main squares, each cluster has a park and there is Dubai Park on Dubai Creek.		
Clubs, golf parks and sports facilities.		
Blue spaces: Dubai Creek and the Arabian Gulf.		
Towers and hotels have a swimming pool on their roof.		

Position	***Images***
Bonds in the golf park.	 
Natural area: Natural plant growth in graveyards and abundant regions.	 

- **Integration of green and grey infrastructure:** The area integrates well with green, blue and grey infrastructure in the urban design while high-rise residential buildings have low integration with green infrastructure, there are large areas of parking lots without any vegetation or shading.
- **Connectivity:** The green network is achieved in the central area of the district while the residential buildings area has less green network (Fig. 4-22).

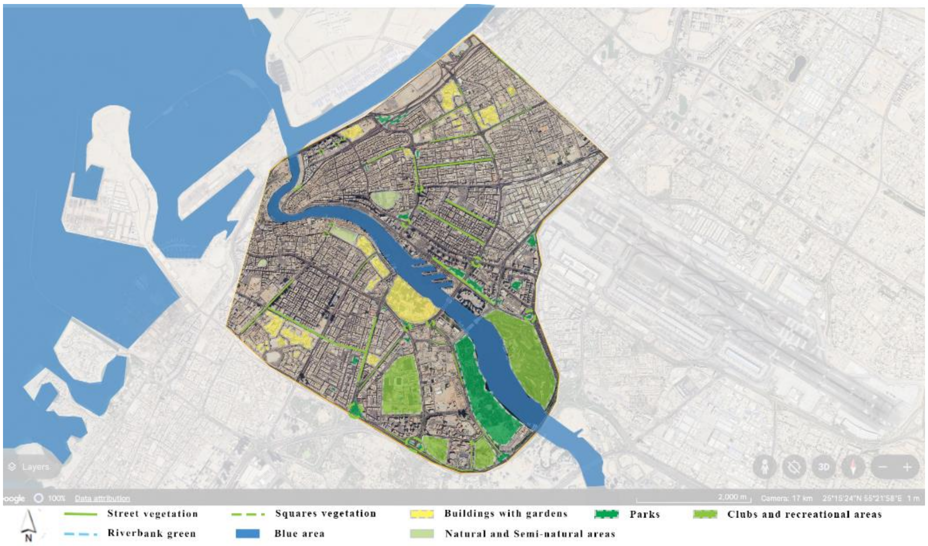


Fig. 4-22 Dubai Green Infrastructure Connectivity Analysis (Source: Author, based on Google Maps)

- **Multifunctionality:** Parks and school facilities provide educational and recreational needs. Private gardens and urban areas reduce noise, provide food, and regulate the climate.

- **Social inclusion:** Environmental awareness enhances social values and fosters cooperation between individuals, non-governmental organizations, and governmental organizations, Dubai 2024 plan the seventh plan, aims to double the green spaces and recreational areas where the first plan was in 1960, the number of population from 1960 til 2020 increase as well as the green spaces in the same period[1].

d. Dubai (study area) Urban Heat Island Analysis

The land surface temperature (LST) of the study area (Fig. 4-23 a, b) and the vegetation index (Fig. 4-23 c) during the summer shows that the urban area is 36˚C to 39.6˚C during the day and 31.5˚C to 33˚C during the night, With 2-3 degrees lower during the day than the very low vegetation areas surrounded and about 1-2˚C during the night, the lands near the Arabian Gulf and canal have lowest LST.

[1] "Dubai 2040 Urban Master Plan," n.d.

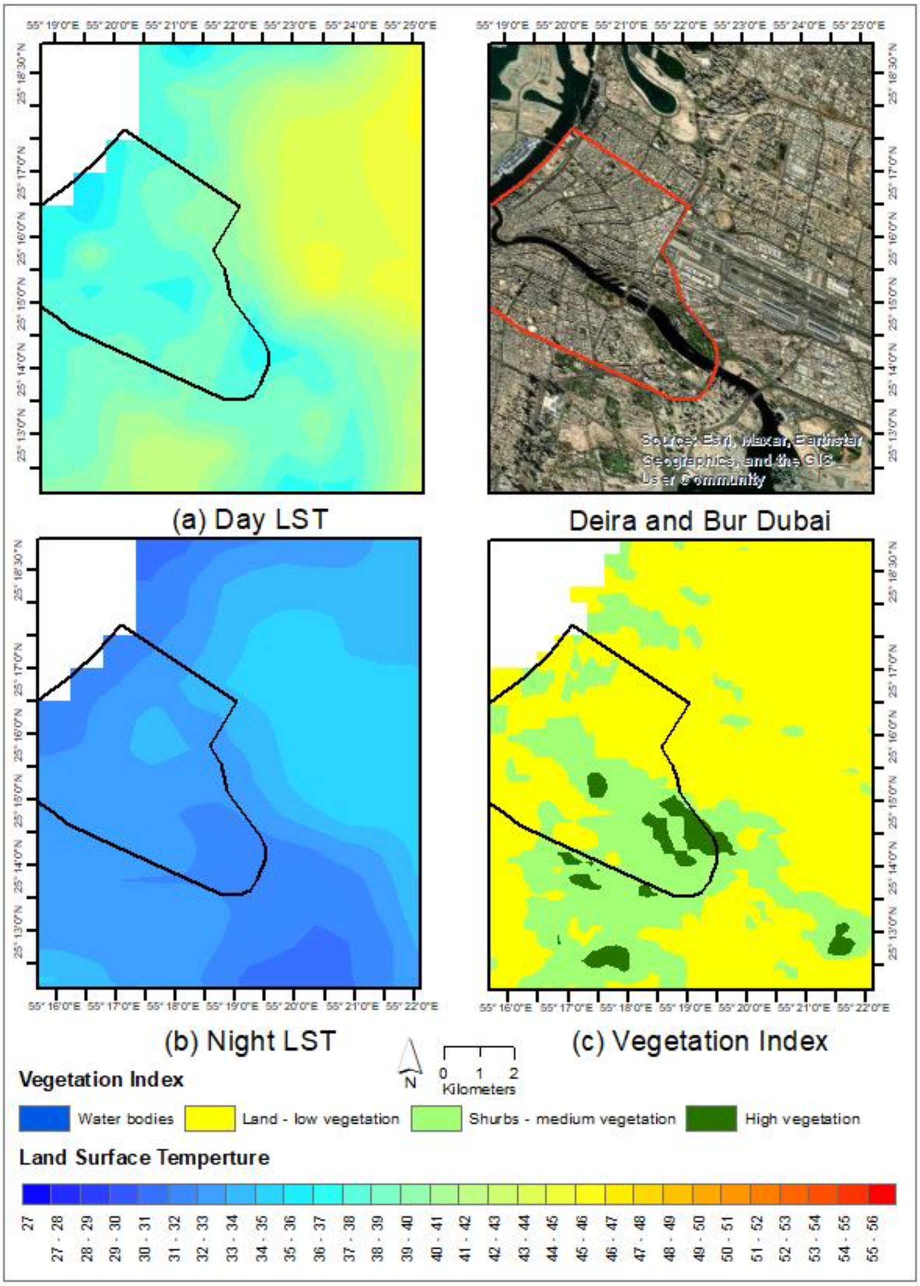


Fig. 4-23 (a) Day LST, (b) Night LST and (c) Vegetation Index thermal maps for Al-Deira and Bur Dubai area on 12 July 2023. (Source: https://ladsweb.modaps.eosdis.nasa.gov/ *,accessed: 2/6/2024*)

It has been observed from Fig. 4-28, The area integrated by water and vegetation has the lowest LST, followed by the land that faces the water surface. At night, both the land facing the water and the area integrated with vegetation have a low LST.

4.3.3. Case 3: Phoenix, Arizona, U.S.A.

The Phoenix metropolitan area, one of the fastest-growing urban regions in the U.S., is located on the northern edge of the Sonoran Desert[1] (Fig. 4-24) (latitude: 33° 26' 54.1536" N; longitude: 112° 4' 26.5296" W). with area 1,338 km^2. Phoenix adopted a master plan in 2010 to create a healthier city through strategic green space investment in response to urban heat island effects and water withdrawal issues. Existing green spaces, on the other hand, vary in size, shape, and vegetation cover, with low-income and ethnic minority neighbourhoods having fewer and smaller green spaces[2]. Encanto Village land use until 2018 is 47% residential, 20% commercial units and 5% parks and open spaces. The village area with 27.2 square km of commercial and high-rise buildings located in the village core[3].

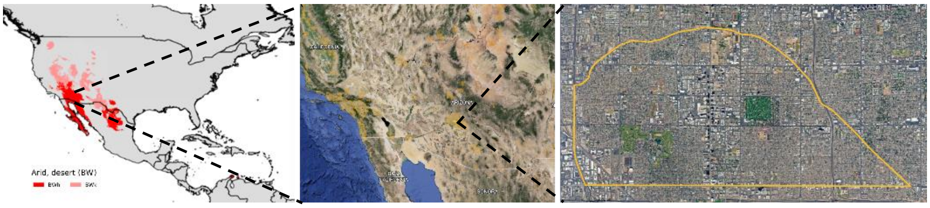


Fig. 4-24 Encanto Village, Phoenix, Arizona, USA. (Study Area). (Source: Google Earth)

a. Phoenix Climatic Parameters

The climate of Pheonix can be classified as typical of hot, subtropical desert climates (Köppen climate classification: BWh). The average annual temperature is 23.2 °C. The rainfall here is around 258 mm per year. The region has mild winters and hot summers. The highest temperature is on July around 41.2 °C with average 34.9 °C, the lowest in December around 4.6 °C and the average around 11.1[4].

b. Phoenix (study area) Urban Parameters

The Encanto Village Planning Committee promotes sustainable food system land use, including community gardens and urban farms, and provides adjacent park/school facilities. They locate land uses with the most intense uses within village cores, centres, and corridors based on village character, needs, and transportation capacity[5].

---

[1] Zhang, Murray, & Turner, 2017, *Optimizing green space locations to reduce daytime and nighttime urban heat island effects in Phoenix, Arizona*, p. 163

[2] *Phoenix , AZ and surrounding area Percent*, 2015, p. 1

[3] Department, 2018, *Encanto Village character plan*, p. 3

[4] "PHOENIX CLIMATE (UNITED STATES OF AMERICA)," n.d.

[5] Department, 2018, *Encanto Village character plan*, p. 10

Fig. 4-25 Residential building. (Source: Google Earth)

Fig. 4-26 Commercial buildings in the village core. (Source: Google Earth)

- **Material properties:** The streets are paved asphalt, and the buildings' external finishing materials: are natural stone, exposed brick, artificial stone white, or earth colours residential buildings have sloped roofs, while commercial buildings and high-rise buildings are curtain walls (Fig. 4-26).
- **Urban geometry:** Streets' widths are more than 10 m to 20 m, and the height of the buildings is from 1-2 floors (Fig. 4-25), while the building in the village core is 10 and 15 floors above the ground[1] (Fig. 4-25, Fig. 4-26).
- **Urban density:** the manned space: 27.2 square km. The estimated population until 2021 will reach about 76,374 inhabitants[2].

c. Phoenix (study area) Green Infrastructure Analysis

Within the principle of protecting village character, the village promotes a pedestrian-friendly environment in centers, including plazas, open spaces, shaded walkways, traffic separation, bicycle parking, and vehicle parking in disguised structures or underground areas[3]. Table 4-6 shows the GI elements distribution in the village.

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[1] Ibid.p. 11
[2] "City-Data.com," n.d.
[3] Department, 2018, *Encanto Village character plan*, p. 12

Table 4-6 Encanto Village, Phoenix green infrastructure elements analysis. (Source: Author, Google Earth Street View photo, https://shorturl.at/jqzvv, accessed 4/7/2024)

Position	***Image***	
Streets - Squares: No main squares with vegetation.		
- Sides: Trees, bioswale and green verge on the street sides.		
- Railroad: The railroad in the car road streets with vegetation on the streetside.		
- Walls: Trees are used as fences.		
Building: Each building has a private garden.		
Parking lots: Trees, bioswale and green verge in parking lots. Not all parking lots have trees.		
Public areas: Public and private parks and open spaces.		

Position	Image	
School sports facilities		
Blue spaces: Grand Canal on the north and east side of the village.		
Pools in high-income neighbourhoods.		
There are bonds inside the park.		
Natural area: The presence of shrubs and some native trees.		

- **Integration of green and grey infrastructure:** The village planning community is focusing on designing and developing pedestrian linkages between parks, open spaces, village cores, and neighbourhood shopping centres, and establishing more neighbourhood parks and green-blue spaces[1].
- **Connectivity:** Provide a pedestrian green network environment with plazas, common open space, shaded walkways, pedestrian and vehicular traffic separation, bicycle parking, and vehicle

[1] Ibid.

parking. Create buffer zones and other amenities to connect new and existing developments[1]. (Fig. 4-27)

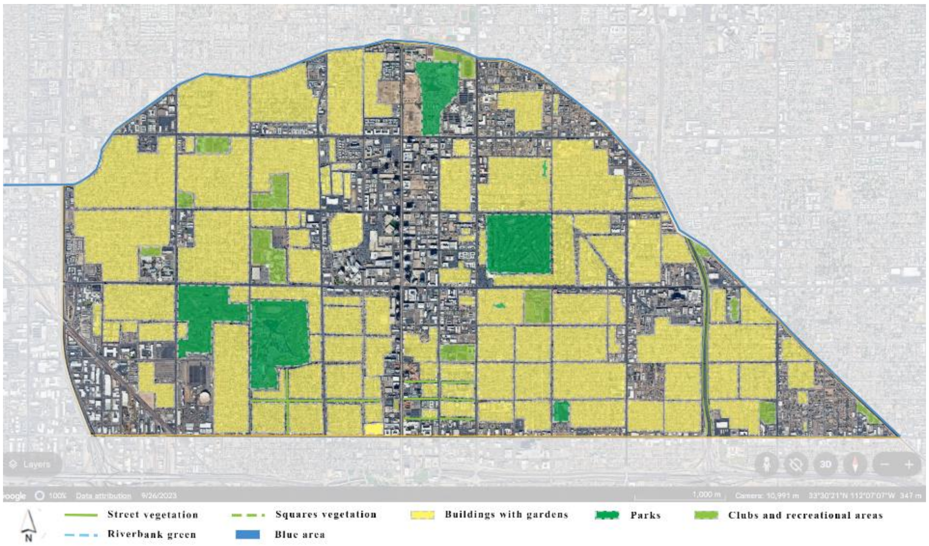

Fig. 4-27 Encanto Green Infrastructure Connectivity Analysis. (Source: Author, based on Google Maps)

- **Multifunctionality:** Parks and school facilities provide educational and recreational needs with no access limit during the school season. While parks and historical districts serve as tourist destinations, private gardens and urban areas reduce noise, provide food, and regulate the climate[2].
- **Social inclusion:** The Encanto Village Planning Committee assisted in identifying specific design principles from the approved 2015 General Plan to better equip all stakeholders with the ability to preserve and protect the Village Character while encouraging growth and investment[3].

d. Phoenix (study area) Urban Heat Island Analysis

The land surface temperature (LST) of Encanto village (Fig. 4-28 a, b) and the vegetation index (Fig. 4-28 c) during the summer the temperature in the Encanto village urban area is 50.7˚C to 53.3˚C during the day and 34.5˚C to 36˚C during the night, With 2-2.5 degrees lower during the day than the very low vegetation areas surrounded and about 1-1.5˚C during the night.

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[1] Ibid.p. 12,13
[2] Ibid.p. 10
[3] Department, 2018, *Encanto Village character plan*

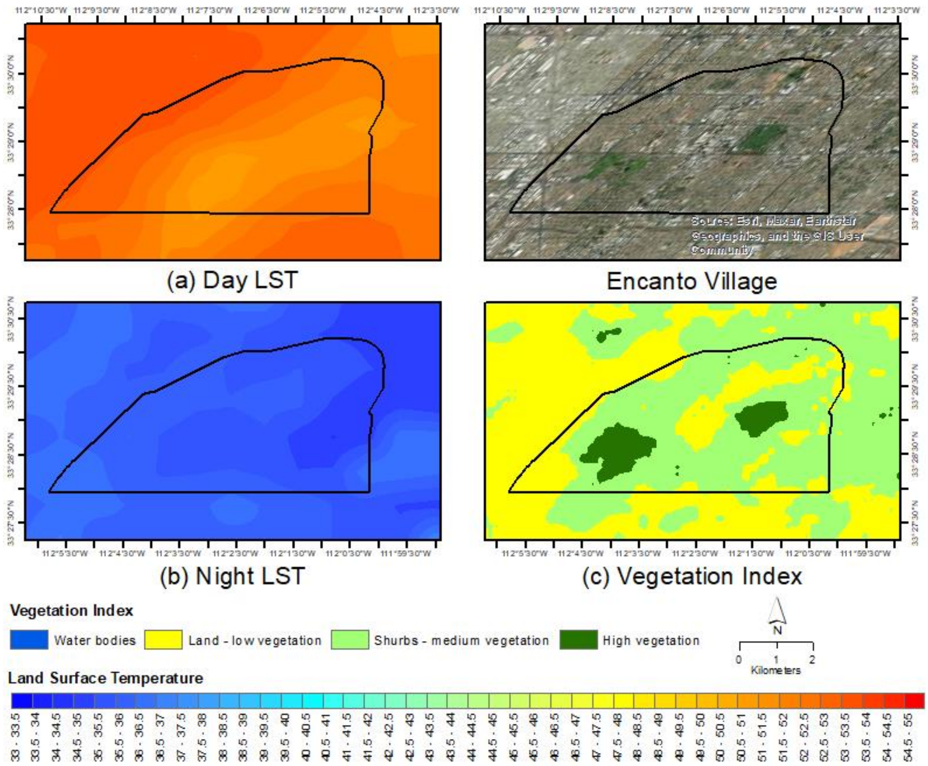

Fig. 4-28 (a) Day LST, (b) Night LST and (c) Vegetation Index thermal maps for Encanto village and surrounding area on 12 July 2023. (Source: https://ladsweb.modaps.eosdis.nasa.gov/ *,accessed: 2/6/2024*)

It has been observed from Fig. 4-28, The area of parks with dense vegetation influences the day LST as it has the lowest LST in the area. The night LST is lowest on the east side, where there is a lot of vegetation, and it gradually rises as the density of vegetation decreases.

4.4. Comparative Analysis of The Cases

Table 4-7 check the green infrastructure principles in each case:

Table 4-7 GI Principles Method Check Analysis in Cities. (Source: Author)

Principles	*Reflection on City*		*Maadi*	*Zamalek*	*Heliopolis*	*Baghdad*	*Dubai*	*Phoenix, Encanto*
Integration of green & grey infrastructure	linking green spaces with (transport – stormwater) infrastructure and buildings		●	●	●	●	●	●
	Tree planting in streets and car parking		●	●	●	○	○	○
	Blue infrastructure complete grey infrastructure		●	●	-	●	●	●
Connectivity	Natural and semi-natural spaces		○	●	○	○	○	○
	Blue spaces		●	●	-	●	●	●
	Green roofs		-	○	-	-	○	-
	Green corridors		●	●	○	●	●	○
	Parks		●	●	●	●	●	○
	Agriculture lands		-	-	-	●	-	-
Multifunctionality	Provisioning services		●	●	●	●	●	●
	Cultural functions and services	Recreation and mental and physical health	●	●	●	●	●	●
		Education and Science	●	●	●	●	●	●
	Biodiversity functions		●	●	●	●	●	●
	Regulating services	Wind buffer	●	●	●	●	●	●
		Noise mitigation	●	●	●	●	●	●
		Temperature regulation	●	●	●	●	●	●
Social inclusion			●	●	●	●	●	●

● ***Match*** ○ Maybe - Don't match

By analyzing the green infrastructure elements and principles achieved in each case. It was found that:

- The Maadi areas managed to achieve grey-green integration and connectivity, it has vegetation and dense tree planting that provide more shading in streets as well as the Nile River that provides evaporation,
- Zamalek's success in green, grey, and blue integration, connectivity, and multifunctionality can be attributed to dense trees and vegetation in streets and building gardens, providing

ample shade, as well as a wide range of clubs, parks and river activities,

- Heliopolis has green-grey infrastructure in the streets while buildings with gardens in a small area in the south,
- Parks in Maadi are in a network with streets unlike Encanto has multiple parks with big areas without linkage or network between them,
- Dubai on the other hand managed to achieve connectivity between green and blue infrastructure but failed in the integration of green-grey infrastructure as it has large parking lots and areas without any vegetation,
- Encanto Village uses vegetation and tree planting in buildings' gardens the most, with large park areas, but the street vegetation is only on the sidewalk,
- Baghdad has green and blue infrastructure, such as orchards and green buildings along the riverbanks, as well as green-grey infrastructure, such as the green belt in the study area's south and the presence of gardens and vegetated streets,
- Baghdad and Heliopolis have trees in the middle of their streets, but they do not provide sufficient shade,
- Agricultural and natural areas with large scale are not observed in the study areas, except for Baghdad's orchards.

Table 4-8 shows the average decrease in temperature in each case according to the vegetation areas.

Table 4-8 The Average Decrease in Temperature According to The Vegetation Areas.

Study areas	***Day temp. Decrease (˚C)***		***Night temp. decrease (C)***		***Average temp. Decrease (C)***	
	Min	*Max*	*Min*	*Max*	*Day*	*Night*
Encanto	2	2.5	1	1.5	2.25	1.25
Dubai	2	3	1	2	2.5	1.5
Baghdad	1	3	1	2	2	1.5
Maadi	2	3	0.5	1	2.5	0.75
Zamalek	1	3	0.5	1	2	0.75
Heliopolis	0.5	2	0.5	1	1.25	0.75

By analysis of the land surface temperature (Table 4-8), it was found that:

- Encanto Parks' area has the lowest temperature in the area of the village,

- In The areas with denser vegetation the LST has decreased compared to surrounding areas with an average temperature about (2˚C) during the day and about (1˚C) at night (Table 4-8),
- Water bodies help decrease the LST of the surrounding areas, especially with vegetation around the water bodies; the Nile River banks in Maadi and Zamalek, Dubai Creek Green Cornish in Dubai and Tigris River in Baghdad,
- Maadi and Zamalek district has the lowest temperature, which can be attributed to the tree density in streets as it gives more shadows than palm trees used in the other cities,
- Dubai area mainly depends on the sea breeze and evaporation from the Golf coast and Dubai Creek, with the presence of vegetated squares and streets.

4.5. Conclusion

This chapter aims to study the effectiveness of green infrastructure principles in reducing urban heat island phenomena in different neighbourhoods in existing cities in the same climatic region (dry-hot climate), by analyzing the green infrastructure (GI) elements and principles in different neighbourhoods and the land surface temperature (LST) of each neighborhood, it was found that:

- The integration of blue infrastructure with large scale (riverbank green – sea breeze) helps in lowering the land surface temperature in urban areas,
- The area with UGI connectivity has the lowest LST,
- The large areas of parks without high GI network reflected on LST in making parks cool island effect,
- The green and blue infrastructure connectivity helps to decrease the LST in the area,
- The use of urban green infrastructure (UGI) connectivity by tree planting with wide shades has high effectiveness in lowering the land surface temperature, thus reducing the urban heat island (UHI) effect,
- The areas with denser vegetation the LST have decreased compared to surrounding areas with an average temperature about (2˚C) during the day and about (1˚C) at night.

Based on the previous analysis implementing green infrastructure elements and adopting its principles in urban planning (integration of green and grey infrastructure and urban green infrastructure connectivity) were found to reach the most optimal thermal performance, the following chapter will apply green infrastructure elements and principles across three areas with similar environmental conditions, contexts, and urban characteristics to identify the most effective scenario for enhancing thermal comfort in existing cities.

CHAPTER 5

APPLIED STUDY

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5.1. Introduction

Adopting the green infrastructure principle offers a framework for conservation that promotes the sustainable use of land. This chapter is an applied study for three areas in El-Mahalla Al-Kubra city, Gharbia Governorate, Egypt, in which different green infrastructure (GI) scenarios are studied and analyzed using the environmental simulation program ENVI-met to identify their effect on thermal performance by analyzing the air temperature, mean radiant temperature (MRT) and the predicted mean vote (PMV), which affect the UHI phenomenon. This study aims to reduce the UHI effect and improve the thermal performance in the city by adopting green infrastructure (GI) principles and demonstrating their effectiveness on the UHI phenomenon. The city was chosen due to the lack of green spaces and the increase of pollutants and industrial areas in the city.

5.2. Study Area Description

El-Mahalla El-Kubra is one of the industrial cities in Egypt. It is located in the middle of the Nile Delta on the western bank of the Damietta branch, Gharbia Governorate, Egypt. It is known for its dominant textile industry (30°57'15"N 31°09'10" E). The climate can be classified as desert climate, The average annual temperature is 21.4°C. the maximum temperature is approximately 35.7°C in July and August, averaging 28.1°C. and the lowest temperature can reach 8.6 °C with an average of 13.6°C [1]. The study is on three areas in the city.

[1] "MAHALLA AL KUBRA CLIMATE," n.d.

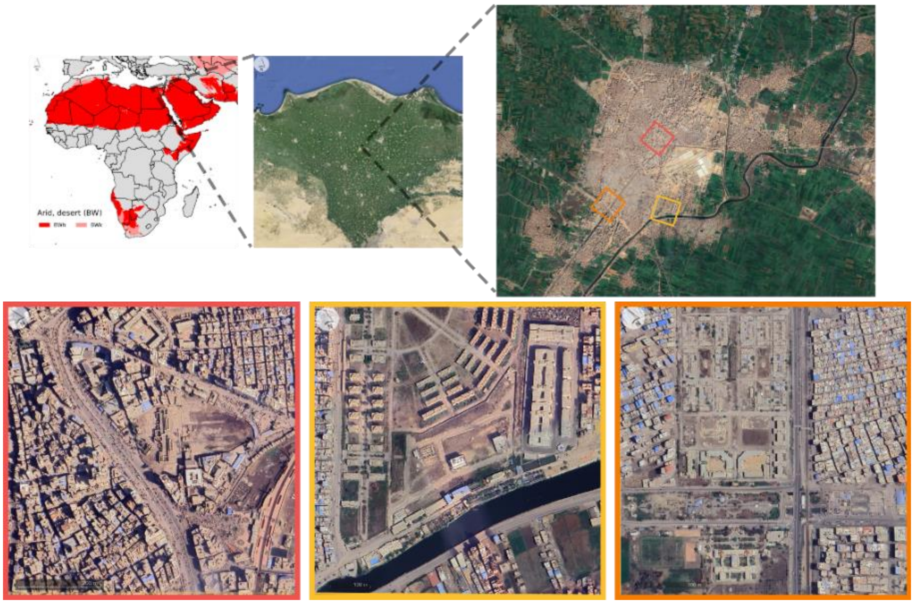


Fig. 5-1 The Study Areas, El-Mahalla El-Kubra, Egypt. (Source: Google Earth)

5.3. Simulation Description

The simulation process in the current study will be carried out using ENVI-met, a computer microclimatic simulation program. Many studies have demonstrated the ENVI-Met's suitability for simulating urban microclimate conditions.

5.4. Simulation Tool Description

The simulation will use ENVI-met 4.0, focusing on the study area's physical configuration and local weather conditions (air temperature, relative humidity, and wind speed and orientation). The program is equipped with the full properties of materials, soil, vegetation, and water, and allows modification based on local specifications within ENVI-met. The LEONARDO model, an application of ENVI-met Headquarter, can produce all outputs.

5.5. Study Area1

The area is the El-Mahalla El-Kubra downtown, the main axis is a main road the eastern part is mainly a commercial area, the eastern part; is located in the north schools and residential areas, in the east located public transportation parking, in the south-east the railway station and the railway station square surrounded by hospitals and street vendors (Fig. 5-2).

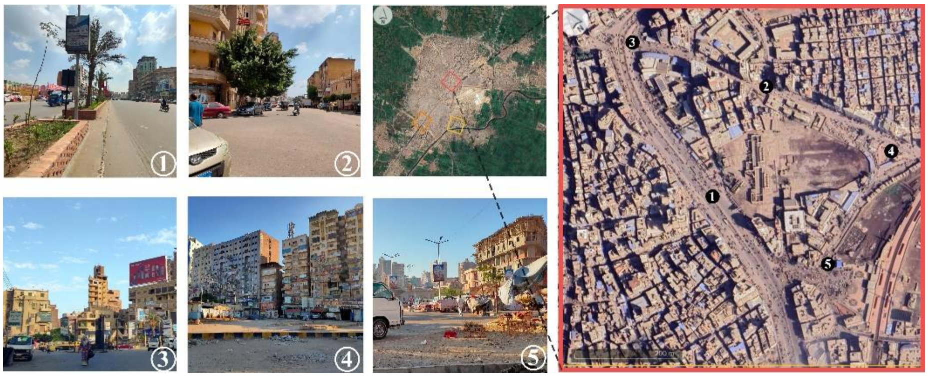


Fig. 5-2 Study Area1, El-Mahalla El-Kubra city. (Source: Google earth, Author 2024)

5.5.1. Study Area1 Simulation Scenarios Description

Three scenarios are proposed to assess the effectiveness of the proposed UGI principles in defining the air temperature and mean radiant temperature (MRT) of the simulation model. All scenarios are modelled in ENVI-met 4.0 applications (Fig. 5-3). Consider the elements used in the analytical study of the same climate region in each scenario.

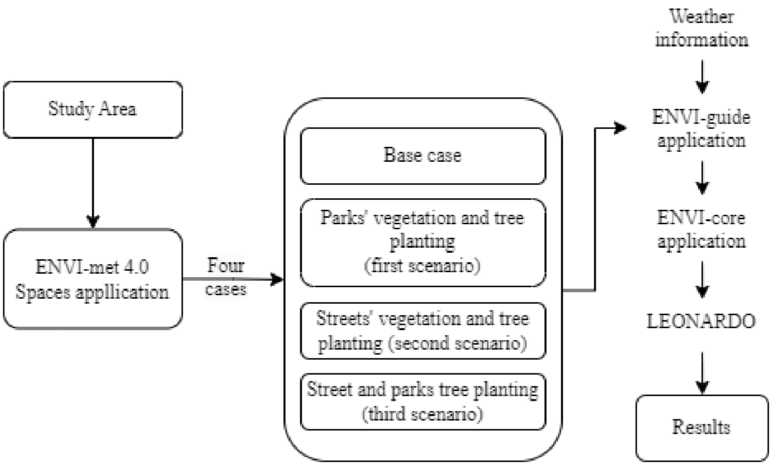


Fig. 5-3 Simulation Description of Assessment of the Effectiveness of UGI in The Study Area 1. (Source: Author)

a. Case 1: Base Case for Area 1:

Refers to the base case of the study area. All related features, whether planted or built, are added as they are in the real world. percentage of green coverage is 1% (Fig. 5-4, a).

b. Case 2: The First Scenario for Area 1 (Parks):

It involves tree planting on existing surfaces, The percentage of green coverage is 6%. This scenario includes the following measures (Fig. 5-4, b):

- Creating a large park with dense grass and trees.
- Vegetated the station square by creating small parks.
- Adding vegetation to the Squares.
- Adding trees in the school's yard and the parking in the public building yard.
- Vegetated the vacant areas.

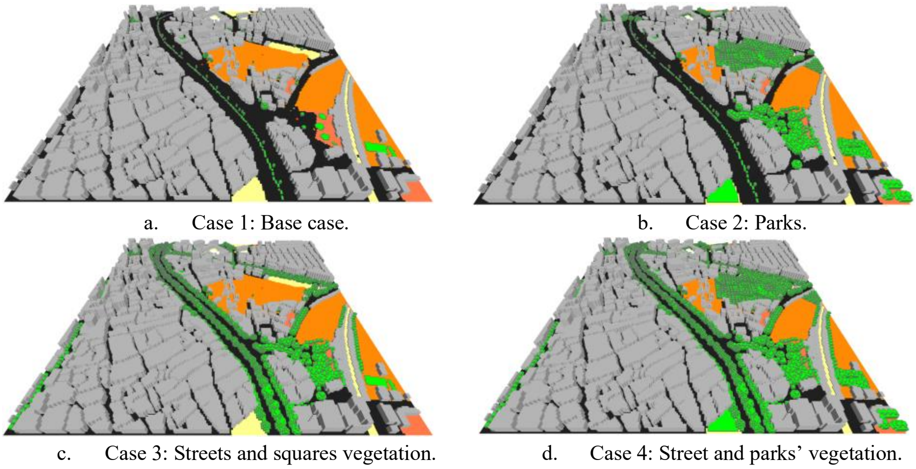
c. Case 3: The Second Scenario for Area 1 (Streets and Squares Tree Planting):

Involves tree planting on existing surfaces, The percentage of green coverage is 15%. This scenario includes the following measures (Fig. 5-4, c):

- Widen the island in the middle of the main street by adding large canopy trees and high-density grass and trees on the sides.
- Vegetated the station square by creating small parks.
- Adding vegetation to the Squares.
- Adding tree canopy to the railway station.

d. Case 4: The Third Scenario for Area 1 (Street and Park Tree Planting):

It involves the greening of the existing surfaces; the percentage of green coverage is 20%. This scenario includes both the measures in the first and second scenarios (Fig. 5-4, d).



a. Case 1: Base case.
b. Case 2: Parks.
c. Case 3: Streets and squares vegetation.
d. Case 4: Street and parks' vegetation.

Fig. 5-4 The Four Cases for Area 1.

5.5.2. Area1 Simulation Settings

The model has an area of about 0.49km2 with the dimensions 700*700m2. Buildings' average height ranges between 4 to 36 m, and the dimensions of the simulation grid for the model domain are 717 (x) * 717 (y)* 75 (z)m. The number of cells at each axis is 239*239*25, while the cell size is 3*3*3m respectively. Model north rotation is 37.7˚, air temperature is 28-39°C, relative humidity is 50-70%, wind speed at the inflow border is 3m/s and the wind direction (constant wind direction at inflow) is 320°. The trees used in the ENVI-met program are represented in Table 5-1.

Table 5-1 The Used Trees in the ENVI-met Program.

Used trees	Height (m)	Crown Width (m)
Cassia Leptophylla	12	7
Koelreuteria Paniculata	10	13
Betula Pendula	6	7
Sophora Japonica	10	15
Palm Washingtonia	20	3
Senegalia Greggii	2	3

5.5.3. Area1 Simulation Results

By simulation the four cases from 10:00 am to 08:00 pm on Summer, 21 July 2023, the following tables show; the air temperature (T_{air}), mean radiant temperature (MRT) and predicted mean vote (PMV) to identify the thermal comfort.

a. Air Temperature (Tair)

By analyzing the air temperature from 10:00 am to 08:00 pm (Table 5-2) the following was found:

The air temperature has decreased in the area in case 3 and case 4 in a noticeable way that case 2 compared to the base case.

- **In the main street:**

Case 2 showed an unnoticeable change from 10:00 am to 08:00 pm compared to Case 1, as for Cases 3 and 4:

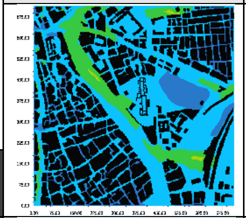
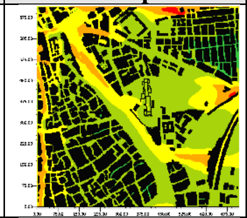
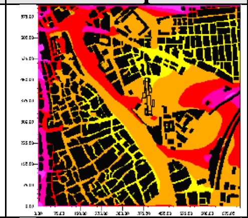
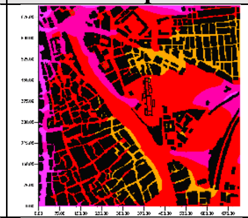
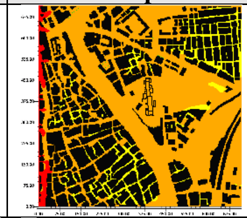
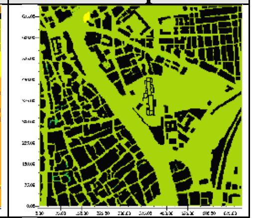
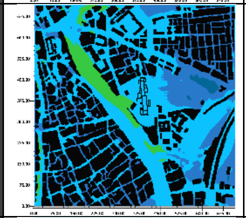
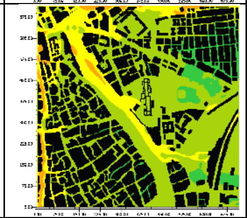
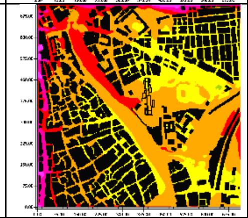
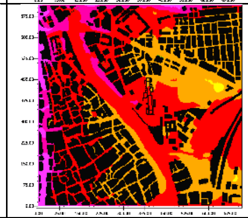
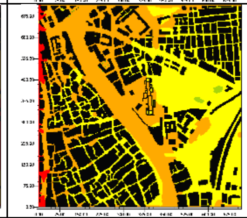
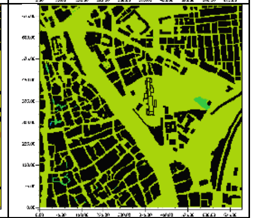
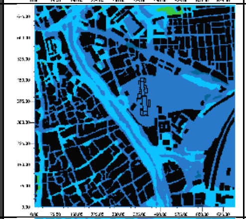
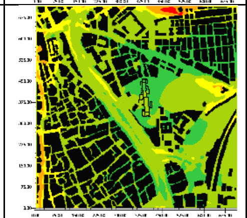
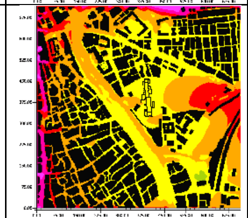
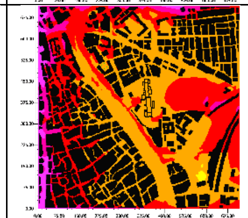
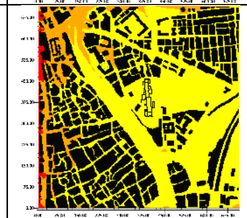
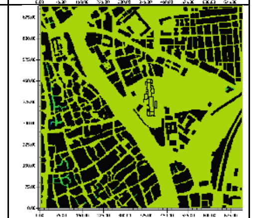
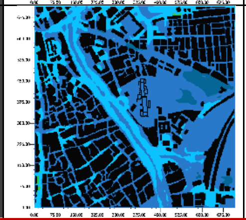
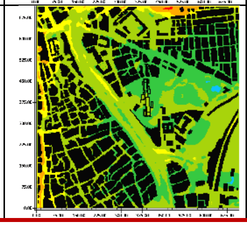
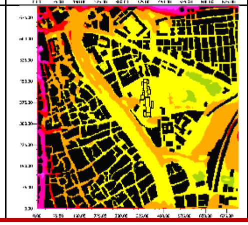
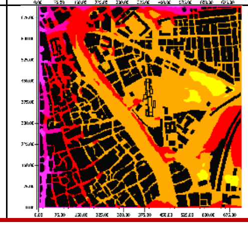
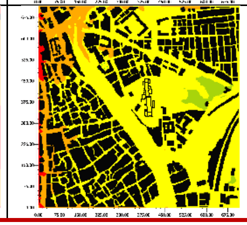
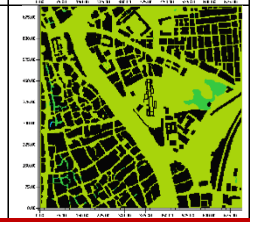
- **At 10:00 am,** Tair decreased compared to Case 1, in Cases 3 and 4 it decreased by 1.5-2.4°C.
- **At noon,** Tair decreased compared to Case 1, in Cases 3 and 4 it decreased by 2.4°C.
- **At 02:00 pm,** till sunset hours 06:00 P.m., Tair decreased compared to Case 1, in Cases 3 and 4 it decreased by 1.5°C.
- **At 08:00 pm,** there was no noticeable change in the four cases.

- **In the public transportation parking area:**

- **at 10:00 am,** T_{air} decreased compared to Case 1, in Cases 2 and 4 by 1.5-3°C, meanwhile, in Case 3 it decreased by 1.5°C.
- **At noon,** T_{air} decreased compared to Case 1, in Cases 2 and 4 by 2.4-3.2°C, meanwhile, in Case 3 it decreased by 1.5°C.

- **At 02:00 pm,** T_{air} decreased compared to Case 1, in Case 2 by 3.2°C, and in Case 3 it decreased by 1.5°C. meanwhile, in Case 4 it decreased by 4°C.
- **At 04:00 pm,** T_{air} decreased compared to Case 1, in Case 2 by 2.4°C, and in Case 3 it decreased by 0.5°C. meanwhile, in Case 4 it decreased by 3.2°C.
- **At sunset hours 06:00 pm,** T_{air} decreased compared to Case 1, in Cases 2 and 3 by 1.5°C, meanwhile, in Case 4 it decreased by 2.4°C.
- **At 08:00 pm,** there was no noticeable change in Cases 2 and 3 while in Case 4 decreased by 1.5°C.

Table 5-2 The Thermal Maps for Air Temperature of (Area1) from 10:00Am to 08:00Pm on 21 July 2023.

Air Temperature unter 31.80 °C 31.80 bis 32.60 °C 32.60 bis 33.40 °C 33.40 bis 34.20 °C 34.20 bis 35.00 °C 35.00 bis 35.80 °C 35.80 bis 36.60 °C 36.60 bis 37.40 °C 37.40 bis 38.20 °C über 38.20 °C	**10:00 am**	**12:00 pm**	**02:00 pm**	**04:00 pm**	**06:00 pm**	**08:00 pm**
Case 1: Base case						
Case 2: Parks' tree planting						
Case 3: Street tree planting.						
Case 4: Street and parks' vegetation. 						

b. Surface temperature (Ts)

- **In the main street:**

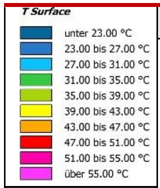
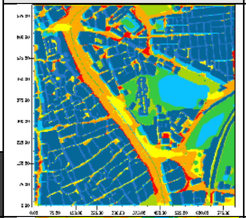
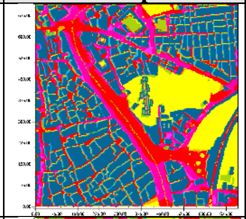
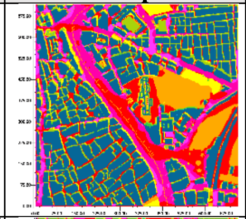
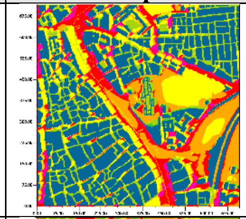
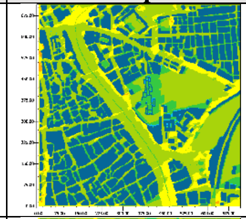
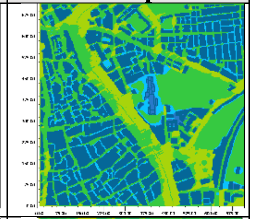
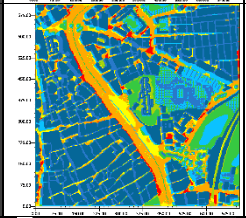
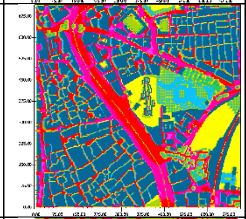
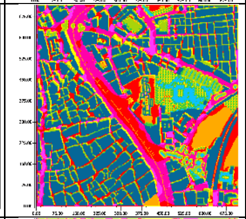
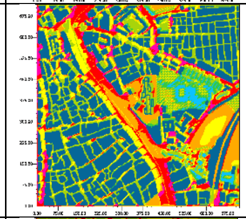
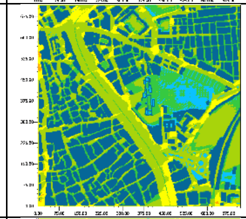
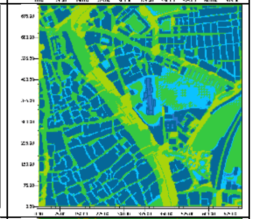
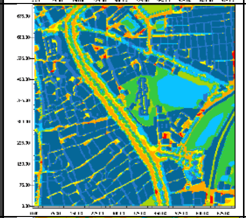
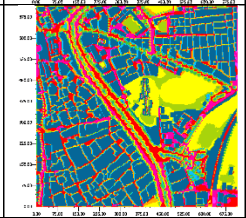
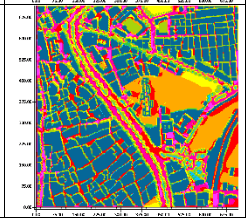
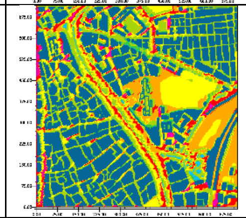
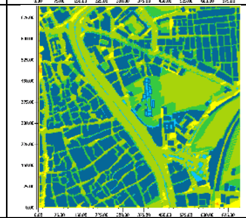
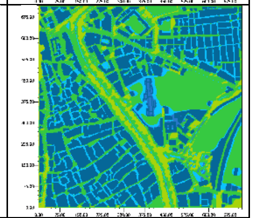
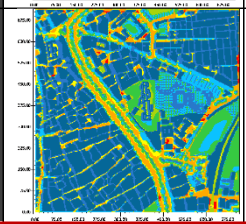
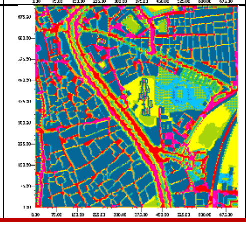
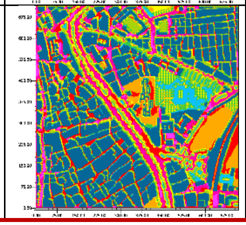
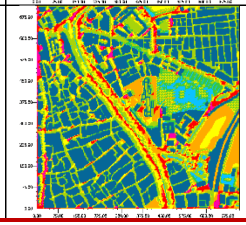
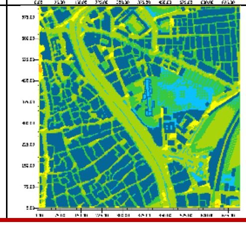
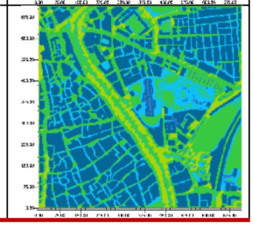
In Case 2 there was no noticeable change from 10:00 am to 08:00 pm compared to Case 1, as for Cases 3 and 4:

- **at 10:00 am,** Ts decreased compared to Case 1, in Cases 3 and 4 it decreased by 12-16°C.
- **At noon,** Ts decreased compared to Case 1, in Cases 3 and 4 it decreased by 16°C.
- **At 02:00 pm,** Ts decreased compared to Case 1, in Cases 3 and 4 it decreased by 16-20°C.
- **At 04:00 pm,** Ts decreased compared to Case 1, in Cases 3 and 4 it decreased by 12°C.
- **At 06:00 pm,** Ts decreased compared to Case 1, in Cases 3 and 4 it decreased by 4-8°C.
- **At 08:00 pm,** Ts decreased compared to Case 1, in Cases 3 and 4 it decreased by 4°C.

- **In the public transportation parking area:**

- **at 10:00 am,** Ts decreased compared to Case 1, in Cases 2 and 4 by 8°C, meanwhile, in Case 3 there is no noticeable change.
- **At noon,** Ts decreased compared to Case 1, in Cases 2 and 4 by 16°C, meanwhile, in Case 3 it decreased by 4°C.
- **At 02:00 pm,** Ts decreased compared to Case 1, in Cases 2 and 4 by 20°C, meanwhile, in Case 3 there is no noticeable change.
- **At 04:00 pm,** Ts decreased compared to Case 1, in Cases 2 and 4 by 16°C, meanwhile, in Case 3 it decreased by 4°C.
- **At sunset hours 06:00 pm,** Ts decreased compared to Case 1, in Cases 2 and 4 by 8-12°C, meanwhile, in Case 3 there is no noticeable change.
- **At 08:00 pm,** there was no noticeable change in Case 3 while in Case 2 decreased by 4°C, and Case 4 decreased by 4-8°C.

Table 5-3 The Thermal Maps for Surface Temperature of (Area 1) from 10:00 Am to 08:00 Pm on 21 July 2023.

	**10:00 am**	**12:00 pm**	**02:00 pm**	**04:00 pm**	**06:00 pm**	**08:00 pm**
Case 1: Base case						
Case 2: Parks' tree planting						
Case 3: Street tree planting.						
Case 4: Street and parks' vegetation. 						

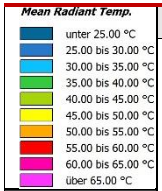
c. Mean Radiant Temperature (MRT)

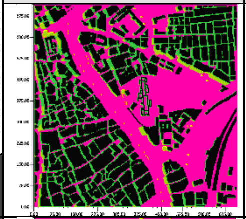
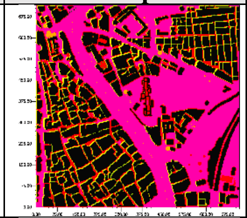
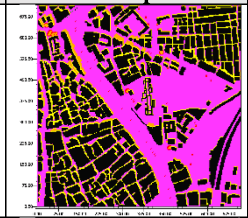
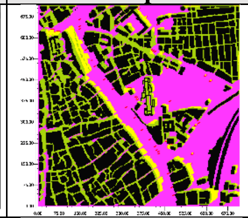
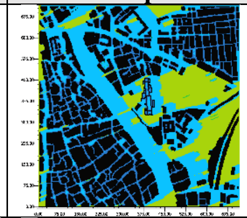
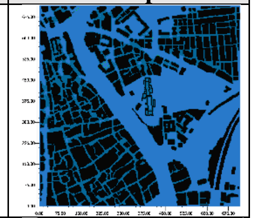
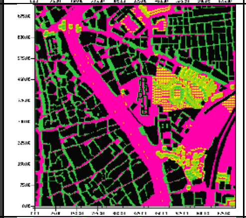
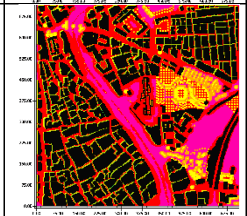
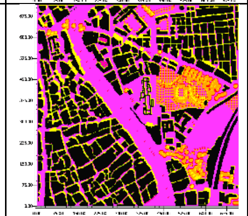
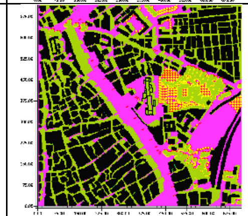
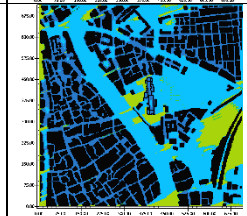
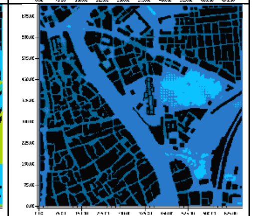
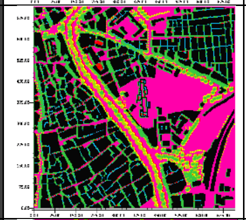
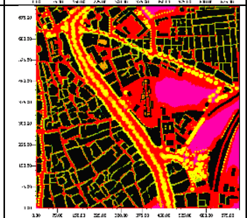
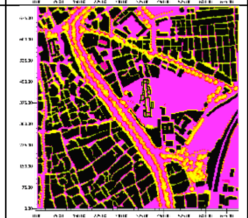
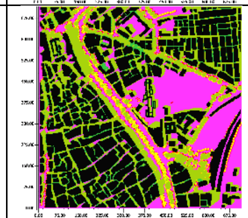
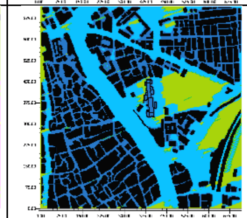
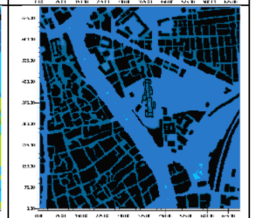
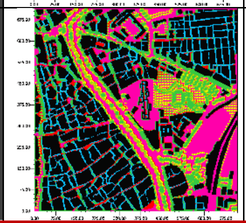
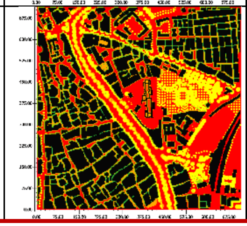
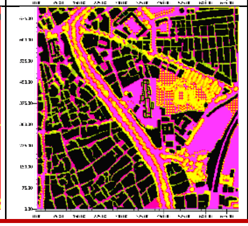
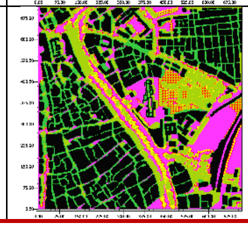
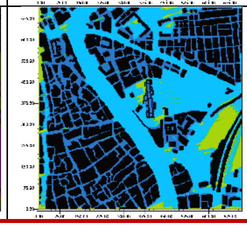
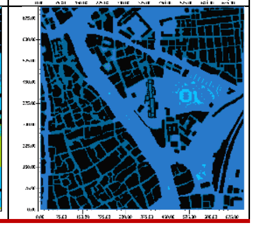
By analyzing the mean radiation temperature (MRT) from 10:00 am to 06:00 pm (Table 5-4) the following was found:

- **In the main street:**
  - **at 10:00 am,** the MRT decreased compared to Case 1, in Cases 3 and 4 it decreased by 25°C, meanwhile, in Case 2 there is no noticeable change.
  - **At noon,** the MRT compared to Case 1, in Case 2 it slightly decreased by 5-10°C, meanwhile, in Case 3 and 4 it decreased by 15°C.
  - **At 02:00 pm,** the MRT decreased compared to Case 1, in Cases 3 and 4 it decreased by 5-25°C, meanwhile, in Case 2 there was no noticeable change.
  - **At 04:00 pm,** the MRT in Case 2 there was no noticeable change compared to Case 1, meanwhile, in Cases 3 and 4 it decreased by 30°C.
  - **At sunset hours 06:00 pm and night at 08:00 pm,** there was no noticeable change in the four cases.

- **In the public transportation parking area:**
  - **At 10:00 am,** the MRT decreased compared to Case 1, in Cases 2 and 4 by 25°C, meanwhile, in Case 3 there was no noticeable change.
  - **At noon,** the MRT decreased compared to Case 1, in Cases 2 and 4 by 20°C, meanwhile, in Case 3 it decreased by 5-10°C.
  - **At 02:00 pm,** the MRT decreased compared to Case 1, in Case 2 by 20°C, and in Case 4 by 25°C, meanwhile, in Case 3 there was no noticeable change.
  - **At 04:00 pm,** the MRT decreased compared to Case 1, in Cases 2 and 4 by 30°C, meanwhile, in Case 3 there was no noticeable change.
  - **At sunset hours 06:00 pm,** the MRT decreased compared to Case 1, in Cases 2 and 4 by 15°C, meanwhile, in Case 3 there was no noticeable change.
  - **At 08:00 pm,** there was no noticeable change in Cases 3 and 4 while the MRT in Case 2 increased by 10°C.

Table 5-4 The Thermal Maps for Mean Radiant Temperature of (Area 1) from 10:00 Am to 08:00 Pm on 21 July 2023.



	10:00 am	12:00 pm	02:00 pm	04:00 pm	06:00 pm	08:00 pm
Case 1: Base case						
Case 2: Parks' tree planting						
Case 3: Street tree planting.						
Case 4: Street and parks' vegetation. 						

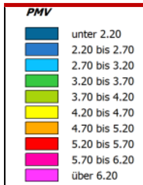
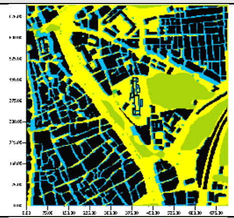
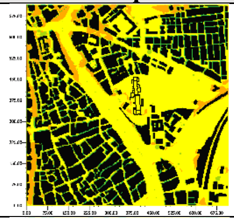
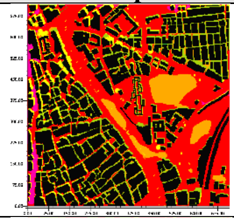
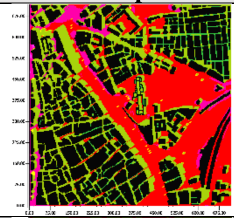
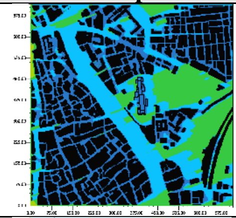
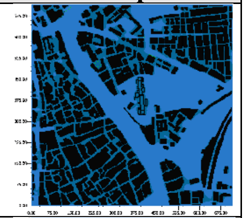
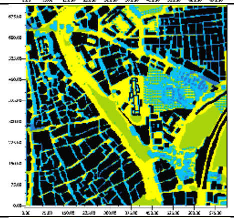
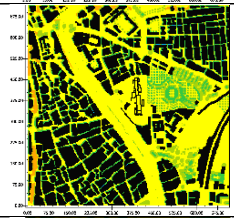
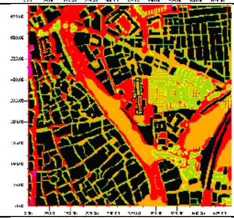
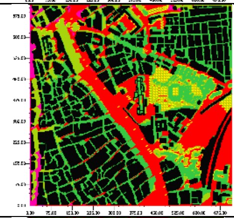
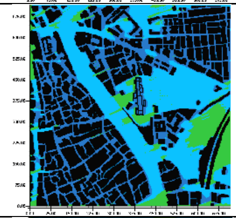
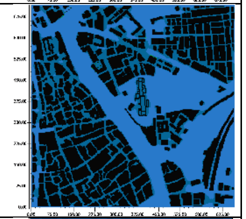
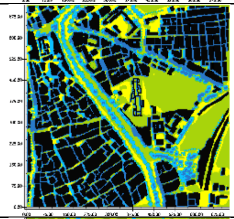
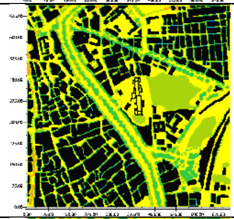
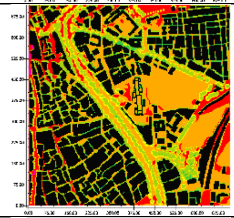
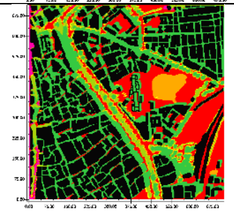
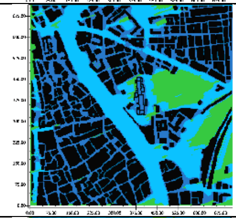
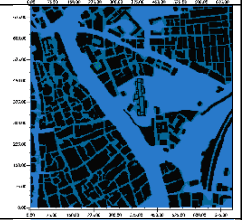
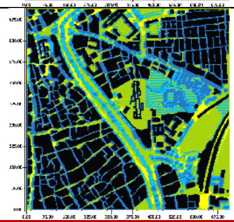
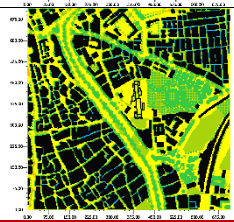
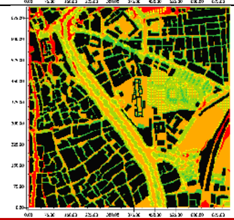
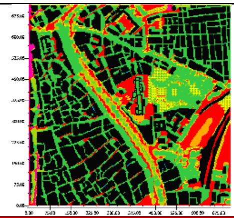
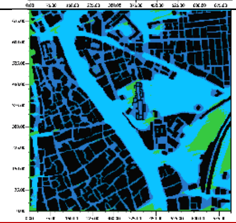
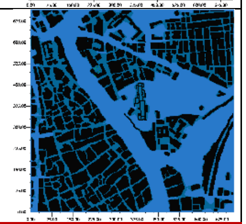
d. Predicted Mean Vote (PMV)

By analyzing the predicted mean vote (PMV) in study area 1 to identify the thermal comfort from 10:00 am to 08:00 pm (Table 5-5), the following was found:

- **In the main street:**
  - **At 10:00 am,** the PMV decreased compared to Case 1, in Case 2 by 1, meanwhile, in Case 3 and 4 it decreased by 1.5-2.
  - **At noon,** the PMV in Case 2 there was no noticeable change, meanwhile, in Case 3 and 4 it decreased by 1.5.
  - **At 02:00 pm,** the PMV decreased compared to Case 1, in Case 2 by 1, meanwhile, in Case 3 and 4 it decreased by 1-2.
  - **At 04:00 pm,** the PMV in Case 2 there was no noticeable change, meanwhile, in Case 3 and 4 it decreased by 2.5.
  - **At sunset hours 06:00 pm and night at 08:00 pm,** there was no noticeable change in the four cases.

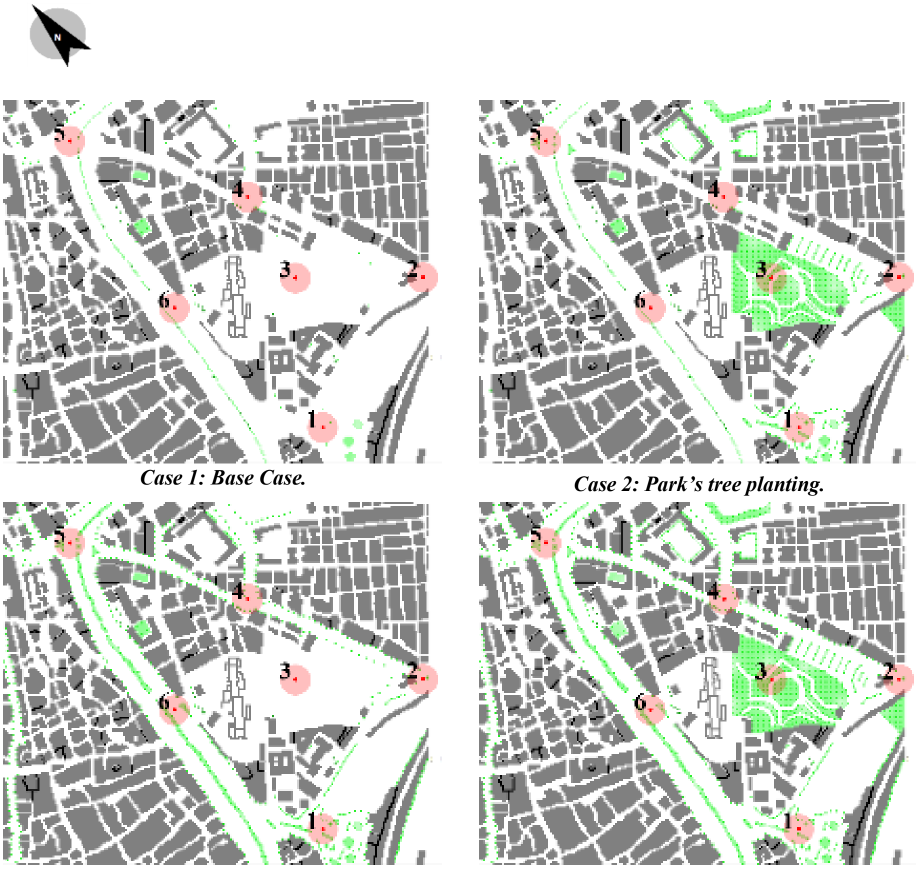
- **In the public transportation parking area:**
  - **at 10:00 am,** the PMV decreased compared to Case 1, in Cases 2 and 4 by 2, meanwhile, in Case 3 it decreased by 1.
  - **At noon,** the PMV decreased compared to Case 1, in Cases 2 and 3 by 1, meanwhile, in Case 4 it decreased by 1.5.
  - **At 02:00 pm,** the PMV decreased compared to Case 1, in Cases 2 and 4 by 1.5-2, meanwhile, in Case 3 it decreased by 1.
  - **At 04:00 pm,** the PMV decreased compared to Case 1, in Cases 2 and 4 by 2.5, meanwhile, in Case 3 it decreased by 1.
  - **At sunset hours 06:00 pm,** the PMV decreased compared to Case 1, in Cases 2 and 4 by 1, meanwhile, in Case 3 there was no noticeable change.
  - **At night 08:00 pm,** there was no noticeable change in the four cases.

Table 5-5 The Thermal Maps for Predicted Mean Vote (PMV) of (Area 1) from 10:00 Am to 08:00 Pm on 21 July 2023.

	**10:00 am**	**12:00 pm**	**02:00 pm**	**04:00 pm**	**06:00 pm**	**08:00 pm**
Case 1: Base case						
Case 2: Parks' tree planting						
Case 3: Street tree planting.						
Case 4: Street and parks' vegetation. 						

5.5.4. Receptors' Points Analysis in Study Area1

Fig. 5-5 show the measurement points' location for comparison between T_{air}, Ts, MRT, and PMV in the four Cases for Area 1, at the main streets, the designed park and the main squares, the points where chosen due to its important positions in the study area, the analysis of each point is shown in Table 5-6 to Table 5-11.



Case 1: Base Case. *Case 2: Park's tree planting.*

Case 3: Street's tree planting *Case 4: Street and parks' vegetation.*

Fig. 5-5 Measurement Points Location for Area 1.

Table 5-6 Point 1 Comparison Between Tair, MRT, and PMV in Area 1.

Case 1: Base Case.

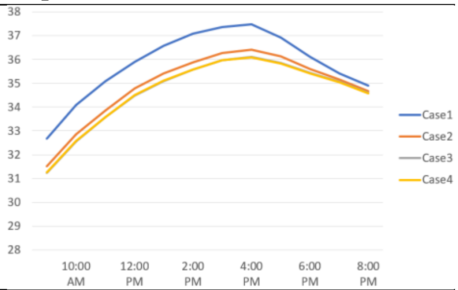
Case 2: Park's tree planting.

Case 3: Street's tree planting.

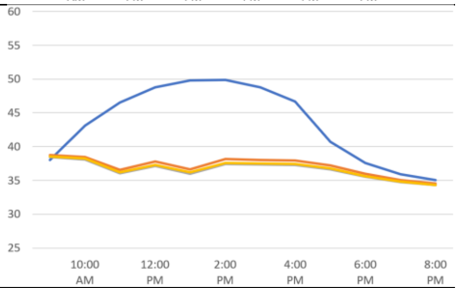
Case 4: Street and parks' vegetation.

POINT 1: Located in the railway station square

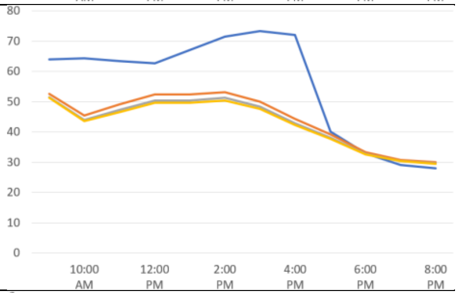
Air Temperature: the maximum rate of decrease compared to Case 1, in Case 2 reached 3.6% at 10:00 am. In comparison, in Cases 3 and 4, the maximum rate of decrease compared to Case 1 reached 4.5% at 10:00 am, The peak hours from 04:00 pm decreased by 1.4°C in Cases 3 and 4 compared to Case 1.



Surface Temperature: the maximum rate of decrease compared to Case 1 was at 01:00 pm, in Case 2 reached 26.4% while in Case 3 reached 27.8% and Case 4 reached 27.4%, The peak hours from 02:00 pm decreased by 13.7°C in Case 4 compared to Case 1.



As for MRT: the maximum rate of decrease compared to Case 1 was at 04:00 pm, in Case 2 reached 38.4% while in Case 3 reached 40.4% and Case 4 reached 41.2%, The peak hour at 04:00 pm in Case 4 decreased by 29.7°C compared to Case 1.



As for PMV: the maximum rate of decrease compared to Case 1 was at 04:00 pm, in Case 2 reached 32.2% while in Case 3 reached 34.3% and Case 4 reached 35.1%, The peak hours from 02:00 to 04:00 pm decreased by 1.2-1.9 in Case 4 compared to Case 1.

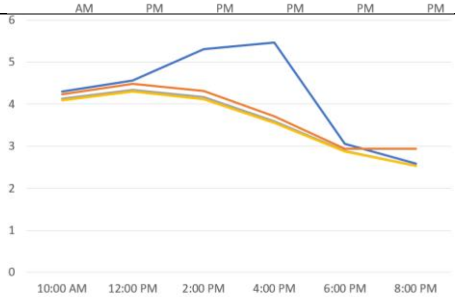
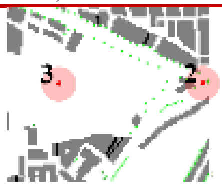


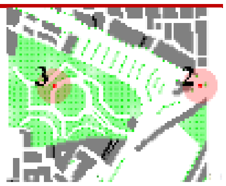
Table 5-7 Point 2 Comparison Between Tair, MRT, and PMV in Area 1.

Case 1: Base Case.

Case 2: Park's tree planting.



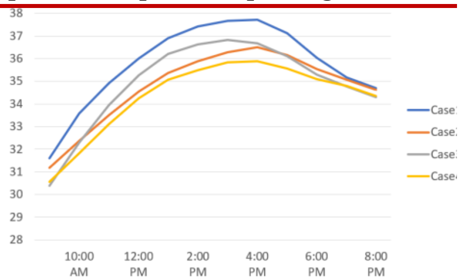
Case 3: Street's tree planting.



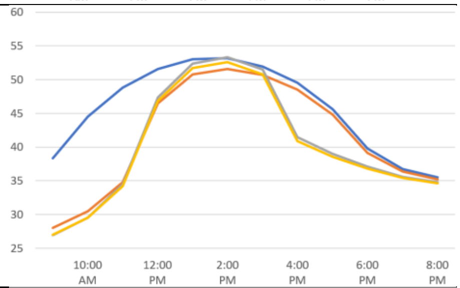
Case 4: Street and parks' vegetation.

POINT 2: Located in the square in the public transportation parking area

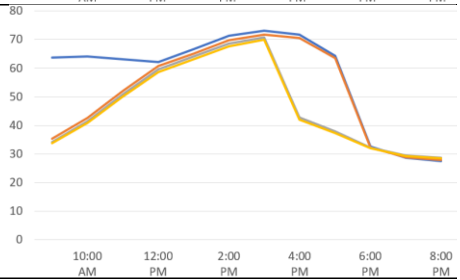
Air Temperature: the maximum rate of decrease in Case 2 is 4.1% compared to Case 1 at 12:00 pm and 02:00 pm, while in Case 3, it decreased by 2.8%. In Case 4, the maximum decrease was 5% from 10:00 am till 04:00 pm, with peak hours at 04:00 pm decreasing by 1.8°C compared to Case 1.



Surface Temperature: the maximum rate of decrease compared to Case 1 was at 10:00 am, in Case 2 reached 31.6% while in Case 3 reached 33.6% and Case 4 reached 33.7%, The peak hours from 02:00 pm decreased by 0.6°C in Case 4 compared to Case 1.



As for MRT: the maximum rate of decrease compared to Case 1, in Case 2 reached 33.5% at 10:00 am while in Case 3 reached 40.3% at 04:00 pm and Case 4 reached 41.5% at 04:00 pm, The peak hours from 02:00 pm till 04:00 pm decreased by 3.6-29.7°C in Case 4 compared to Case 1.



As for PMV: the maximum rate of decrease compared to Case 1 was at 10:00 am, in Case 2 reached 38% while in Case 3 reached 39.6% and Case 4 reached 42%, The peak hours from 02:00 to 04:00 pm decreased by 1.1-1.5 in Case 4 compared to Case 1.

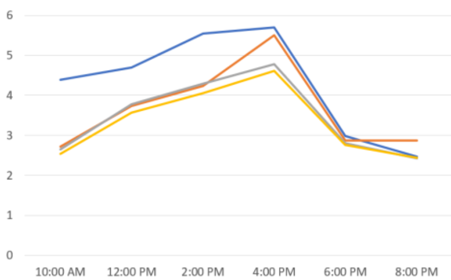
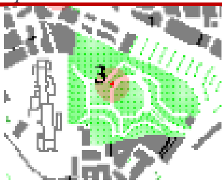
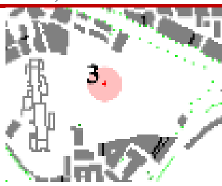
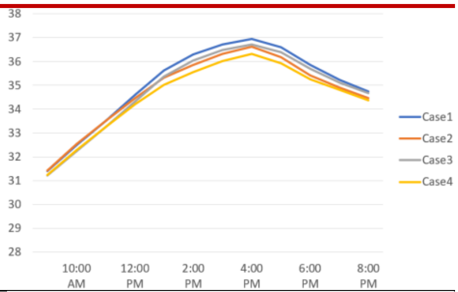


Table 5-8 Point 3 Comparison Between Tair, MRT, and PMV in Area 1.

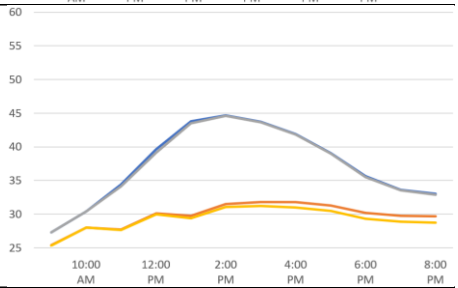
			
Case 1: Base Case.	*Case 2: Park's tree planting.*	*Case 3: Street's tree planting.*	*Case 4: Street and parks' vegetation.*

POINT 3: Located in the vacant area

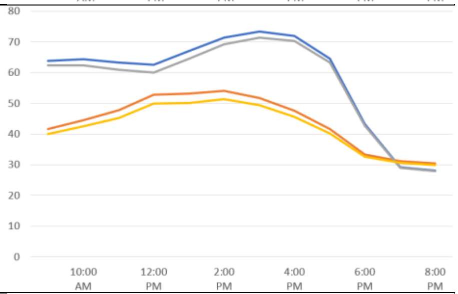
Air Temperature: the maximum rate of decrease compared to Case 1, in Case 2 reached 1.2% at 02:00 pm, while in Case 3 the maximum rate of decrease reached 0.8% at noon, meanwhile in Case 4 the maximum rate of decrease reached 2.1% at 02:00 pm The peak hours from 02:00 to 04:00 pm decreased by 0.8°C in Case 4 compared to Case 1.



Surface Temperature: the maximum rate of decrease compared to Case 1 was at 02:00 pm, in Case 2 reached 29.5% while in Case 3 reached 0.2% and Case 4 reached 30.5%, The peak hours from 02:00 pm decreased by 13.6°C in Case 4 compared to Case 1.



As for MRT: the maximum rate of decrease compared to Case 1, in Case 2 reached 33.8% at 04:00 pm while in Case 3 reached 4.1% at noon and Case 4 reached 36.6% at 04:00 pm, The peak hours from 02:00 pm till 04:00 pm decreased by 20.2-26.4°C in Case 4 compared to Case 1.



As for PMV: the maximum rate of decrease compared to Case 1, in Case 2 reached 29.7% at 04:00 pm, while in Case 3 reached 4.3% at noon, and Case 4 reached 33% at 04:00 pm, The peak hours from 02:00 to 04:00 pm decreased by 1.2-1.7 in Case 4 compared to Case 1.

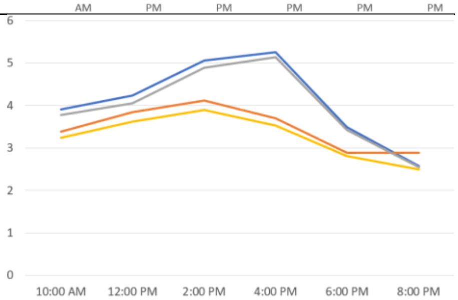
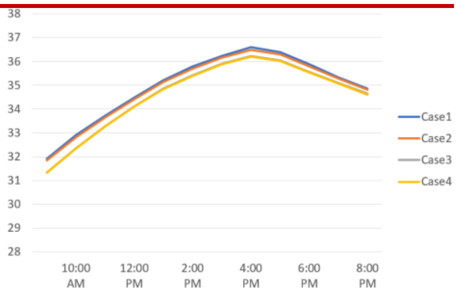


Table 5-9 Point 4 Comparison Between Tair, MRT, and PMV in Area 1.

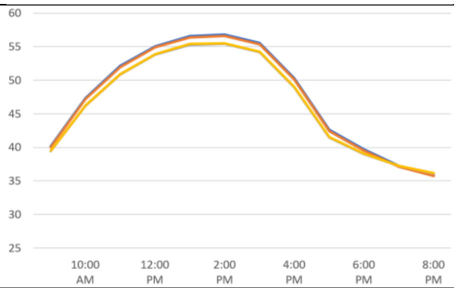
			
Case 1: Base Case.	*Case 2: Park's tree planting.*	*Case 3: Street's tree planting.*	*Case 4: Street and parks' vegetation.*

POINT 4: Located in the middle of the sub-street

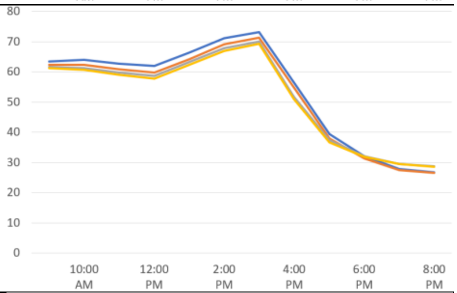
Air Temperature: the rate of decrease in Case 2 is 0.3% compared to Case 1 from 10:00 am till 06:00 pm, while in Cases 3 and 4 the maximum rate of decrease is 1.6% at 10:00 am. The peak hour at 04:00 pm decreased by 0.4°C compared to Case 1.



Surface Temperature: the maximum rate of decrease compared to Case 1 was at 02:00 pm, in Case 2 reached 0.4% while in Case 3 reached 2.4% and Case 4 reached 2.3%, The peak hours from 02:00 pm decreased by 1.3°C in Case 4 compared to Case 1.



As for MRT: the maximum rate of decrease compared to Case 1, in Case 2 reached 3.5% at noon, while in Case 3 reached 8.3% at 04:00 pm and Case 4 reached 9.6% at 04:00 pm, The peak hours at 02:00 pm decreased by 4.3°C in Case 4 compared to Case 1.



As for PMV: the maximum rate of decrease compared to Case 1, in Case 2 reached 2.7% at noon, while in Case 3 reached 20.8% at 04:00 pm, and Case 4 reached 22.2% at 04:00 pm, The peak hours from 02:00 to 04:00 pm decreased by 0.3-1.1 in Case 4 compared to Case 1.

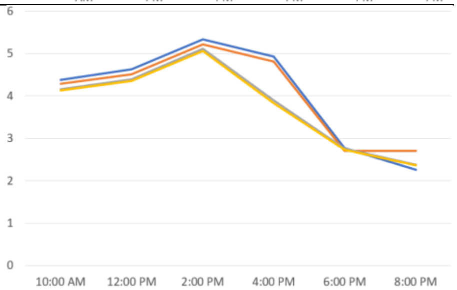
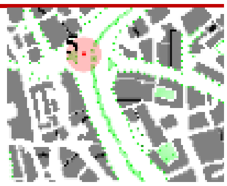


Table 5-10 Point 5 Comparison Between Tair, MRT, and PMV in Area 1.

Case 1: Base Case.

Case 2: Park's tree planting.

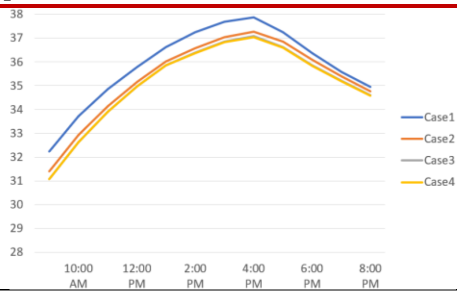
Case 3: Street's tree planting.



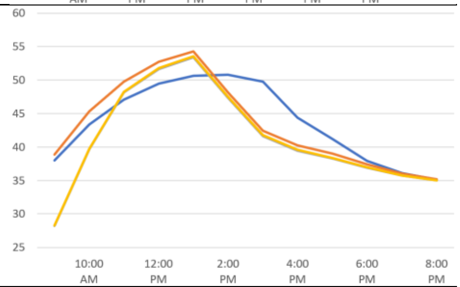
Case 4: Street and parks' vegetation.

POINT 5: Located in the main street square

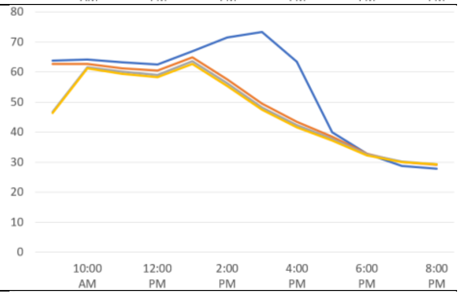
Air Temperature: the maximum rate of decrease compared to Case 1 was at 10:00 am, in Case 2 reached 2.3%. In comparison, in Cases 3 and 4 reached 3.2%, The peak hour at 04:00 pm decreased by 0.8°C in Cases 3 and 4 compared to Case 1.



Surface Temperature: the maximum rate of decrease compared to Case 1 was at 03:00 pm, in Case 2 reached 14.7% while in Case 3 reached 16.3% and Case 4 reached 16.1%, The peak hours from 02:00 pm decreased by 3.3°C in Case 4 compared to Case 1.



As for MRT: the maximum rate of decrease compared to Case 1 was at 04:00 pm, in Case 2 reached 31.5% while in Case 3 reached 33.4% and Case 4 reached 34.5%, The peak hours at 04:00 pm in Case 4 decreased by 21.9°C compared to Case 1.



As for PMV: the maximum rate of decrease compared to Case 1 was at 04:00 pm, in Case 2 reached 32.2% while in Case 3 reached 33.8% and Case 4 reached 34.7%, The peak hour at 04:00 pm decreased by 2 in Case 4 compared to Case 1.

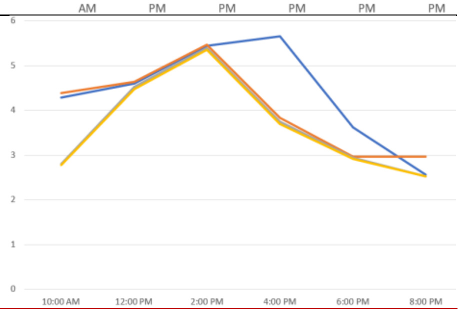
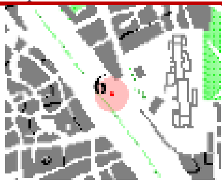
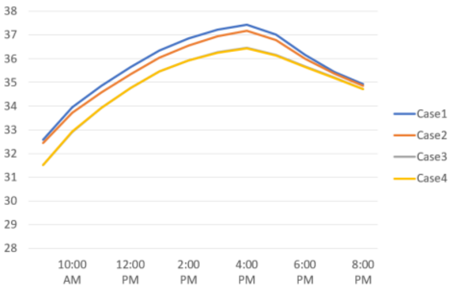
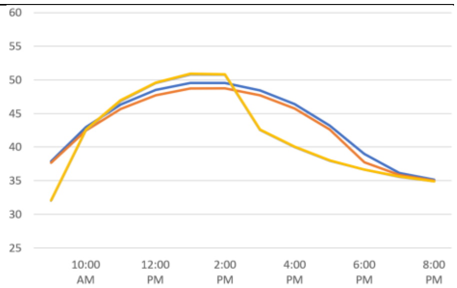
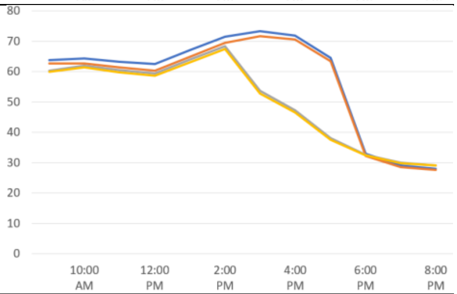
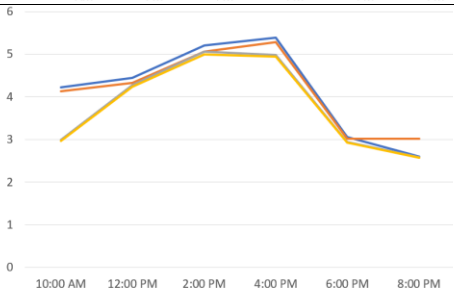


Table 5-11 Point 6 Comparison Between Tair, MRT, and PMV in Area 1.

			
Case 1: Base Case.	*Case 2: Park's tree planting.*	*Case 3: Street's tree planting.*	*Case 4: Street and parks' vegetation.*

POINT 6: Located in the middle of the main street

Air Temperature: the maximum rate of decrease compared to Case 1, in Case 2 reached 0.8% at 12:00 pm and 02:00 pm, while in Case 3 the maximum rate of decrease reached 2.6% at 04:00 pm, meanwhile in Case 4 the maximum rate of decrease reached 2.7% at 04:00 pm The peak hour 04:00 pm decreased by 1°C in Cases 3 and 4 compared to Case 1.	
Surface Temperature: the maximum rate of decrease compared to Case 1 was at 04:00 pm, in Case 2 reached 1.4% while in Case 3 reached 13.8% and Case 4 reached 13.7%, The peak hours at 02:00 pm increased by 1.3°C in Case 4 compared to Case 1.	
As for MRT: the maximum rate of decrease compared to Case 1, in Case 2 reached 0.4% at noon, while in Case 3 reached 34.4% at 04:00 pm and Case 4 reached 35.4% at 04:00 pm, The peak hours at 02:00 pm to 04:00 pm decreased by 25.5°C in Case 4 compared to Case 1.	
As for PMV: the maximum rate of decrease compared to Case 1, in Case 2 reached 2.8% at noon, while in Case 3 reached 29.2% at 10:00 am, and Case 4 reached 29.8% at 10:00 am, The peak hours from 02:00 pm to 04:00 pm decreased by 0.2-0.4 in Cases 3 and 4 compared to Case 1.	

Adding trees in streets improved the thermal performance in streets and surrounding areas, and adding trees in the park improved the thermal performance in the park affecting nearby streets. However, adding trees in streets and parks has the most optimal thermal performance in the entire area.

5.6. Study Area2

The area is located in the south-east of the city, the area characterized by the waterway, on the north bank; clubs and recreational areas, on the south bank; there are residential and agricultural land, and the remaining areas are mainly residential neighborhood designed with poorly green spaces, the eastern building is the industrial development authority a governmental building (Fig. 5-6).

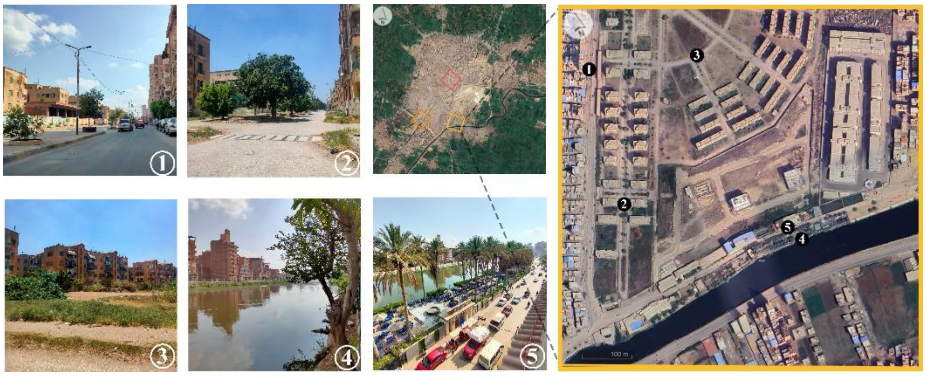


Fig. 5-6 Study Area2, El-Mahalla El-Kubra city. (Source: Google Earth, Author 2024)

5.6.1. Study Area2 Simulation Scenarios Description

Three scenarios are proposed to assess the effectiveness of the proposed UGI principles in defining the air temperature and mean radiant temperature (MRT) of the simulation model. All scenarios are modelled in ENVI-met 4.0 applications (Fig. 5-7). Consider the elements used in the analytical study of the same climate region in each scenario.

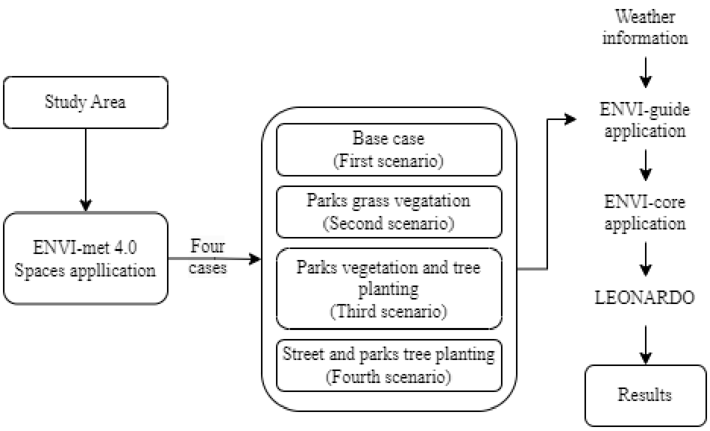


Fig. 5-7 Simulation Description of Assessment of the Effectiveness of UGI in Study Area 2. (Source: Author)

a. Case 1: Base Case for Area 2:

Refers to the base case of the study area. All related features, whether planted or built, are added as they are in the real world. The percentage of green coverage is 10% (Fig. 5-8, a).

b. Case 2: The First Scenario for Area 2 (Grass):

It involves tree planting on existing surfaces, The percentage of green coverage is 25%. This scenario includes the following measures (Fig. 5-8, b):

- Adding dense grass to the residential neighborhood's parks.
- Adding dense grass to the industrial area vacant land.
- Adding dense grass street island in the main street.

c. Case 3: The Second Scenario for Area 2 (Parks Tree Planting):

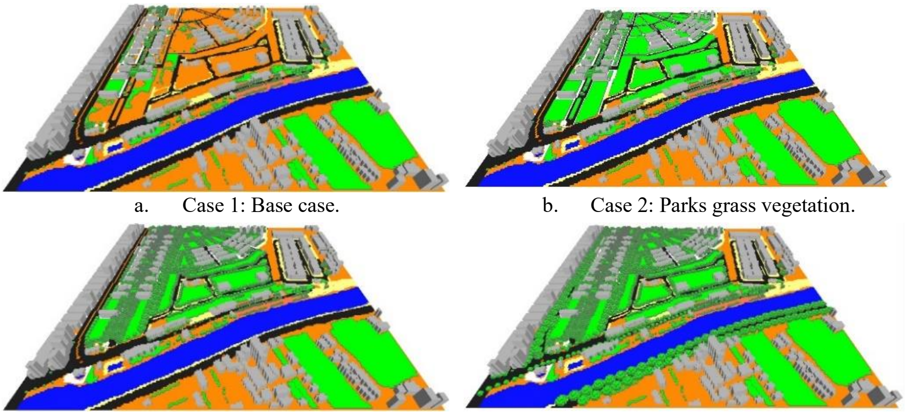
Following the green infrastructure principles, which Involve greening the existing surfaces, the percentage of green coverage is 25%. This scenario includes the following measures (Fig. 5-8, c):

- Adding dense grass and trees to the residential neighborhood's parks and streets.
- Adding dense grass and trees to the industrial area vacant land.

d. Case 4: The Third Scenario for Area 2 (Street and Parks Tree Planting):

Following the green infrastructure principles, which involve greening the existing surfaces, the percentage of green coverage is 35%. This scenario includes the following measures (Fig. 5-8, d):

- Adding dense grass and trees to the residential neighborhood's parks and streets.
- Exchange the small trees with large crown trees to give more shadow.
- Adding dense grass and trees to the industrial area vacant land.
- Adding tree canopy and high-density grass in the middle and sides of the streets.
- Adding large canopy trees and high-density grass on the sides of the waterway bank.



a. Case 1: Base case.

b. Case 2: Parks grass vegetation.

c. Case 3: Parks tree planting and vegetation.

d. Case 4: Street and parks vegetation.

Fig. 5-8 The Four Cases for Area 2.

5.6.2. Area2 Simulation Settings

The model has an area of about 0.49km^2 with the dimensions 700*700m^2. Buildings' average height ranges between 4 to 36 m, and the dimensions of the simulation grid for the model domain are 717 (x) * 717 (y)* 75 (z)m. The number of cells at each axis is 239*239*25, while the cell size is 3*3*3m respectively. Model north rotation is 19˚, air temperature is 28-39°C, relative humidity is 50-70%, wind speed at the inflow border is 3m/s and the wind direction (constant wind direction at inflow) is 320°. The trees used in the ENVI-met program are represented in Table 5-12.

Table 5-12 The Used Trees in the ENVI-met Program for Area 2.

Used trees	Height (m)	Crown Width (m)
Koelreuteria Paniculata	10	13
Betula Pendula	6	7
Palm Washingtonia	20	3
Senegalia Greggii	2	3
Sophora Japonica	10	15

5.6.3. Area2 Simulation Results

By simulation of the four cases from 10:00 am to 08:00 pm on Summer, 21 July 2023, the following tables show; the air temperature (Ta), mean radiant temperature (MRT) and predicted mean vote (PMV) to identify the thermal comfort.

a. Air Temperature (Tair)

By analyzing the air temperature from 10:00 am to 08:00 pm (Table 5-13) the following was found:

The air temperature has slightly increased in Case 2 by adding grass only compared to the current situation in Case 1. Meanwhile, the air temperature decreased significantly in Cases 3 and 4 by planting trees in parks and streets compared to Case 1.

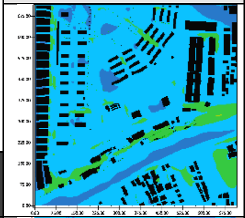
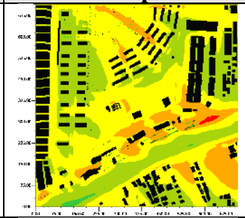
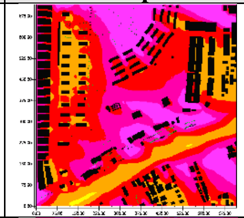
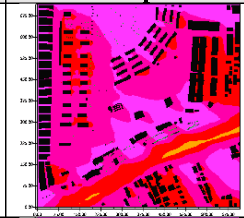
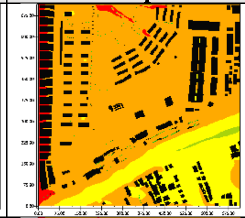
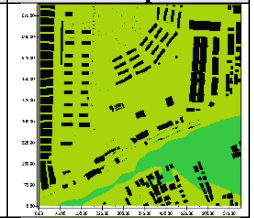
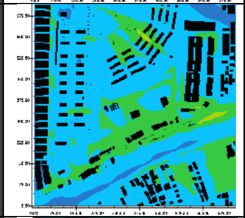
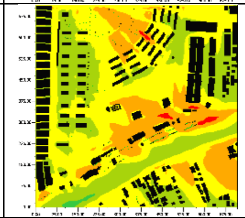
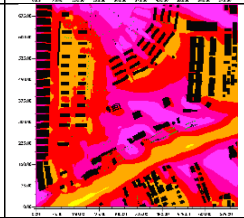
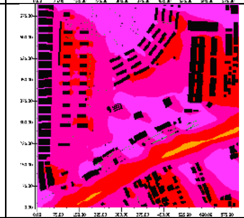
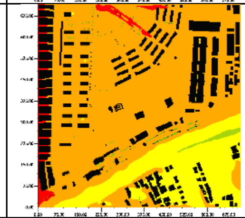
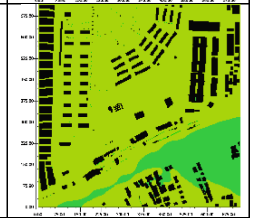
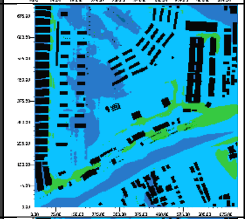
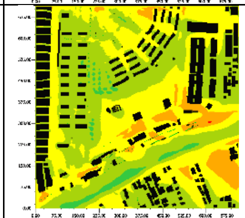
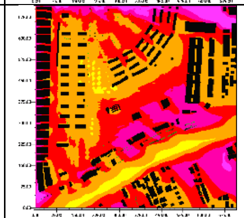
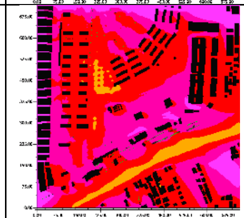
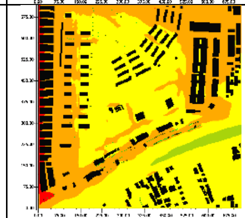
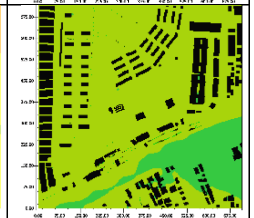
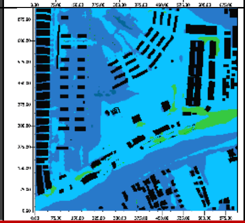
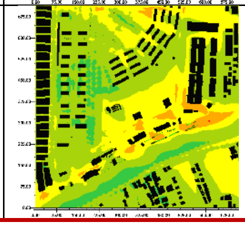
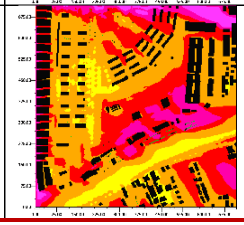
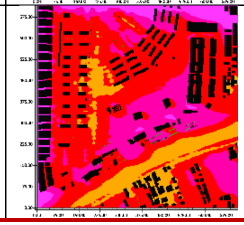
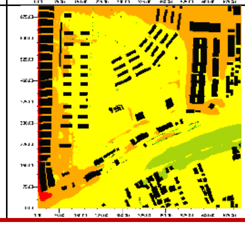
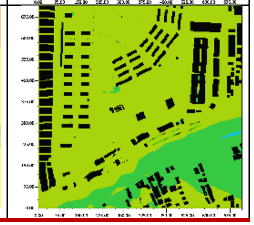
- **In streets:**

Compared to Case 1, Case 2 showed unnoticeable change all day, while Case 3 and 4:

  - **At 10:00 am,** compared to Case 1, Cases 2 and 3 showed unnoticeable change, while Case 4 decreased by 0.8°C.
  - **From noon till 02:00 pm,** compared to Case 1, Case 3 slightly decreased near the river by 0.8°C. Meanwhile, Case 4 decreased by 0.8-1.6°C.
  - **At 04:00 pm,** compared to Case 1, Case 3 slightly decreased near the river less than 0.8°C. Meanwhile, Case 4 decreased by 0.8-1.6°C and 1.6-2.4°C near the river.
  - **At 06:00 pm,** compared to Case 1, Case 3 slightly decreased near the river less than 0.8°C. Meanwhile, Case 4 decreased by 0.8°C and 0.8-1.6°C near the river.
  - **At 08:00 pm,** it unnoticeably changed in the three cases.

- **In parks:**
  - **From 10:00 am till noon,** Tair increased in Case 2 by 1.6°C compared to Case 1, meanwhile, it decreased in Cases 3 and 4 by 1.6°C.
  - **At 02:00 pm,** compared to Case 1, Case 2 unnoticeably changed. Meanwhile, it decreased in Cases 3 and 4 by 1.6-2.4°C.
  - **At 04:00 and 06:00 pm,** compared to Case 1, Case 2 unnoticeably changed. Meanwhile, it decreased in Cases 3 and 4 by 0.8-1.6°C.
  - **At 08:00 pm,** it unnoticeably changed in the three cases.

Table 5-13 The Thermal Maps for Air Temperature of (Area1) from 10:00 Am to 08:00 Pm on 21 July 2023.

Air Temperature unter 31.80 °C 31.80 bis 32.60 °C 32.60 bis 33.40 °C 33.40 bis 34.20 °C 34.20 bis 35.00 °C 35.00 bis 35.80 °C 35.80 bis 36.60 °C 36.60 bis 37.40 °C 37.40 bis 38.20 °C über 38.20 °C	**10:00 am**	**12:00 pm**	**02:00 pm**	**04:00 pm**	**06:00 pm**	**08:00 pm**
Case 1: Base case						
Case 2: Parks' tree planting						
Case 3: Street tree planting.						
Case 4: Street and parks' vegetation. 						

b. Surface temperature (Ts)

By analyzing the surface temperature (Ts) from 10:00 am to 08:00 pm (Table 5-14), the following was found:

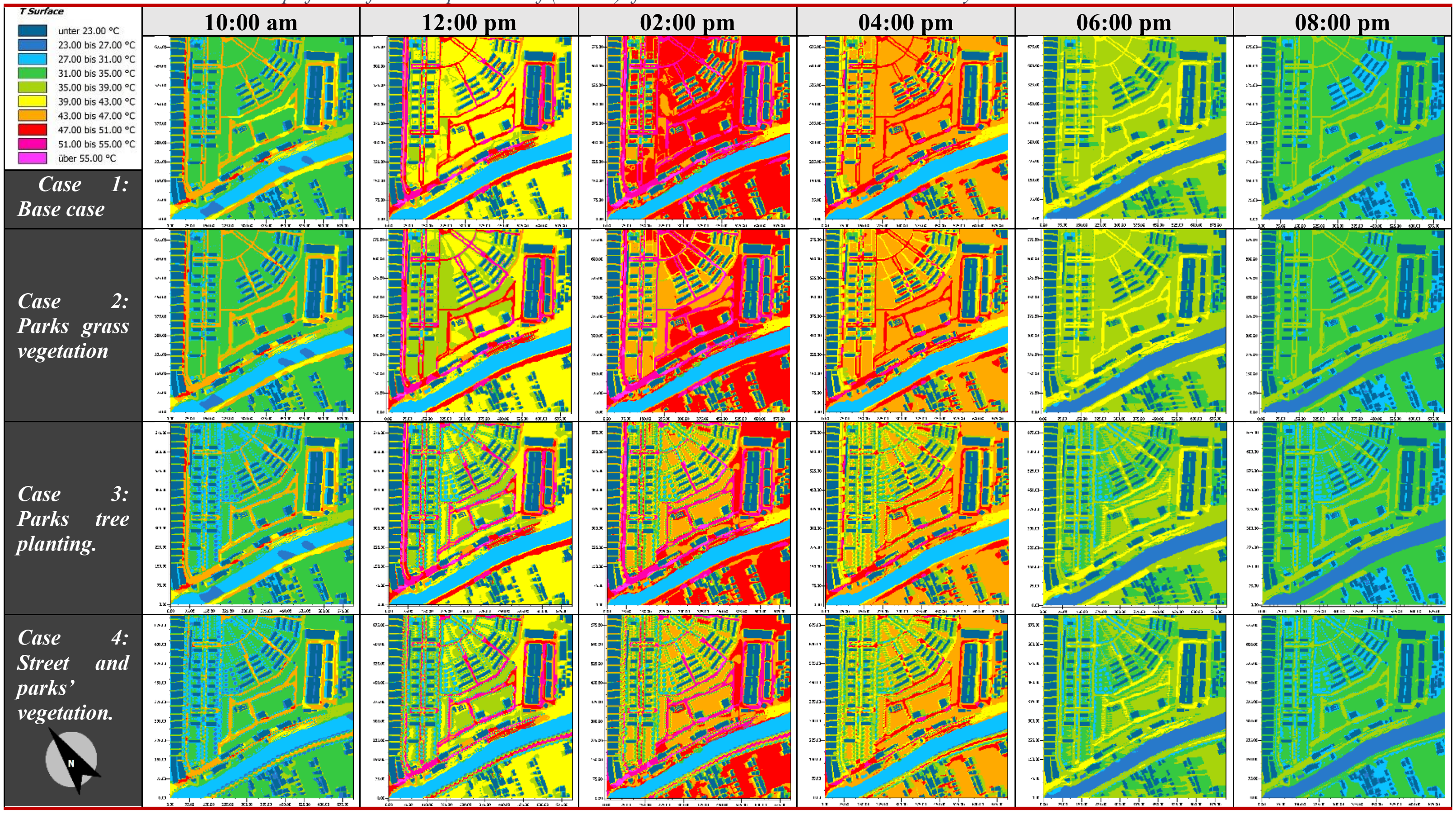
- **In streets:**

Compared to Case 1, the Ts was unnoticeably changed all day in Cases 2 and 3, while Case 4:

- **From 10:00 am till 02:00 pm**, compared to Case 1, Case 4 decreased by 16-20°C.
- **At 04:00 pm**, compared to Case 1, Case 4 decreased by 8-12°C.
- **At sunset hours 06:00 pm and 08:00 pm**, compared to Case 1, Case 4 decreased by 4-8°C.

- **In parks:**
  - **At 10:00 am**, the Ts was unnoticeably changed in Case 2 compared to Case 1, while Cases 3 and 4 decreased by 8°C.
  - **At noon**, the Ts in Case 2 decreased by 8°C, while in Case 3 and 4 it decreased by 8-16°C compared to Case 1.
  - **At 02:00 pm**, the Ts in Case 2 decreased by 8°C, while in Case 3 and 4 it decreased by 8-24°C compared to Case 1.
  - **At 04:00 pm**, the Ts in Case 2 unnoticeably changed, while in Case 3 and 4 it decreased by 8-20°C compared to Case 1.
  - **At sunset hours 06:00 pm**, the Ts was unnoticeably changed in Case 2, while Case 3 and 4 decreased by 8-12°C compared to Case 1.
  - **While at 08:00 pm** there is no noticeable change in Case 2; in cases 3 and 4 it decreased by 8°C.

Table 5-14 The Thermal Maps for Surface Temperature of (Area 2) from 10:00 Am to 08:00 Pm on 21 July 2023.



c. Mean Radiant Temperature (MRT)

By analyzing the mean radiation temperature (MRT) from 10:00 am to 08:00 pm (Table 5-15), the following was found:

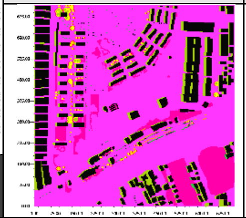
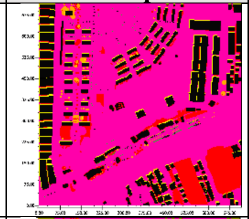
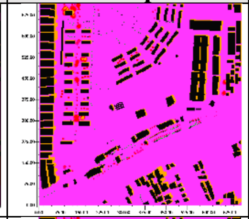
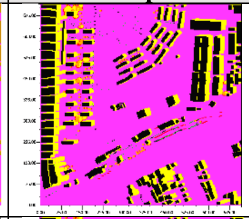
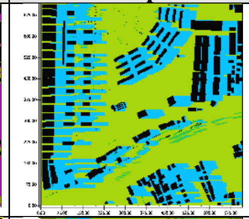
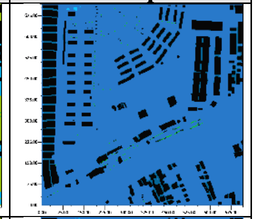
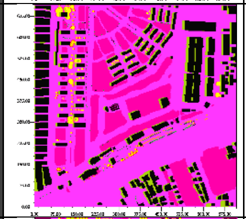
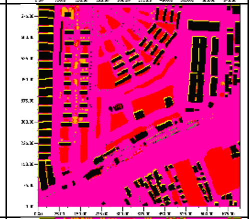
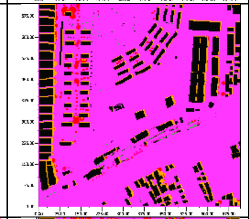
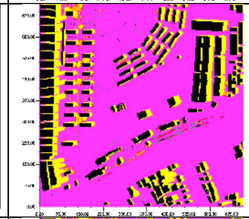
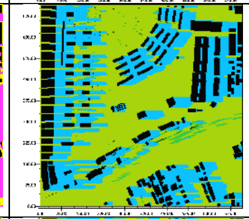
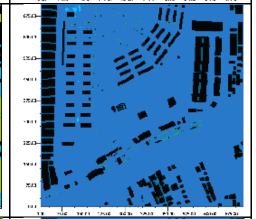
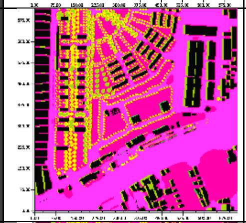
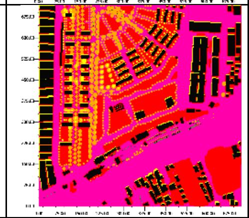
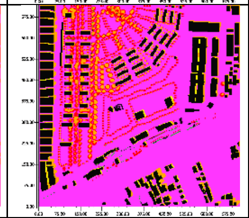
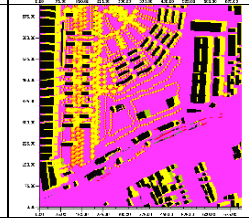
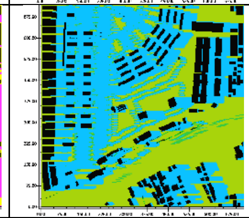
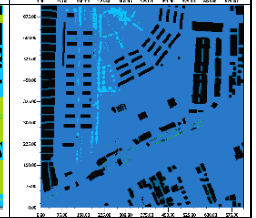
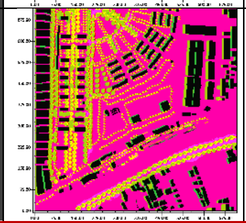
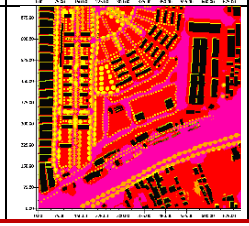
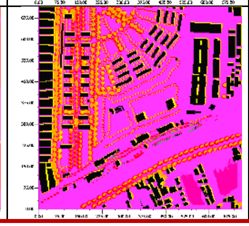
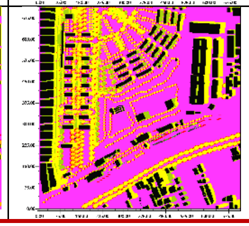
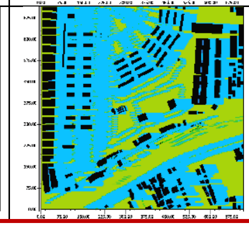
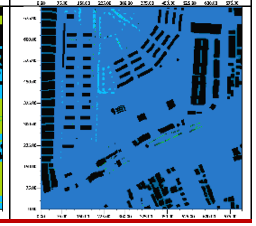
- **In streets:**

Compared to Case 1, Cases 2 and 3 showed unnoticeable change all day, while Case 4:

- **At 10:00 am,** compared to Case 1, the MRT decreased in Case 4 by 20-25°C.
- **At noon,** compared to Case 1, Case 4 decreased by 15-20°C.
- **At 02:00 pm,** compared to Case 1, Case 4 decreased by 15-20°C and 5°C near the river.
- **At 04:00 pm,** compared to Case 1, Case 4 decreased by 5-10°C and 15-20°C near the river.
- **At 06:00 pm,** compared to Case 1, Case 4 decreased by 10-15°C near the river.
- **While at 08:00 pm,** it unnoticeably changed in the three cases.

- **In parks:**
  - **At 10:00 am,** the MRT increased in Case 2 by 5°C, while in Cases 3 and 4 it increased in the unshaded areas by 5°C while in the shaded areas decreased by 25°C compared to Case 1.
  - **At noon,** the MRT in Case 2 decreased slightly by 5°C, while in Case 3 and 4 it decreased by 5-20°C compared to Case 1.
  - **At 02:00 pm,** the MRT was unchanged in Case 2, while Case 3 and 4 decreased by 5-10°C compared to Case 1.
  - **At 04:00 pm,** the MRT was unchanged in Case 2, while Case 3 decreased by 5-20°C and Case 4 decreased by 5-25°C compared to Case 1.
  - **At sunset hours 06:00 pm,** the MRT was unnoticeably changed in Case 2, while Case 3 and 4 decreased by 15°C compared to Case 1.
  - **While at 08:00 pm,** there is no noticeable change in case 2 while in cases 3 and 4 it decreased slightly by 5°C.

Table 5-15 The Thermal Maps for Mean Radiant Temperature of (Area 2) from 10:00 Am to 08:00 Pm on 21 July 2023.

Mean Radiant Temp. unter 25.00 °C 25.00 bis 30.00 °C 30.00 bis 35.00 °C 35.00 bis 40.00 °C 40.00 bis 45.00 °C 45.00 bis 50.00 °C 50.00 bis 55.00 °C 55.00 bis 60.00 °C 60.00 bis 65.00 °C über 65.00 °C	**10:00 am**	**12:00 pm**	**02:00 pm**	**04:00 pm**	**06:00 pm**	**08:00 pm**
Case 1: Base case						
Case 2: Parks' tree planting						
Case 3: Street tree planting.						
Case 4: Street and parks' vegetation.						

d. Predicted Mean Vote (PMV)

By analyzing the predicted mean vote (PMV) to identify the thermal comfort from 10:00 am to 08:00 pm (Table 5-16) the following was found:

- **In streets:**

Compared to Case 1, Case 2 showed unnoticeable change all day, while Cases 3 and 4:

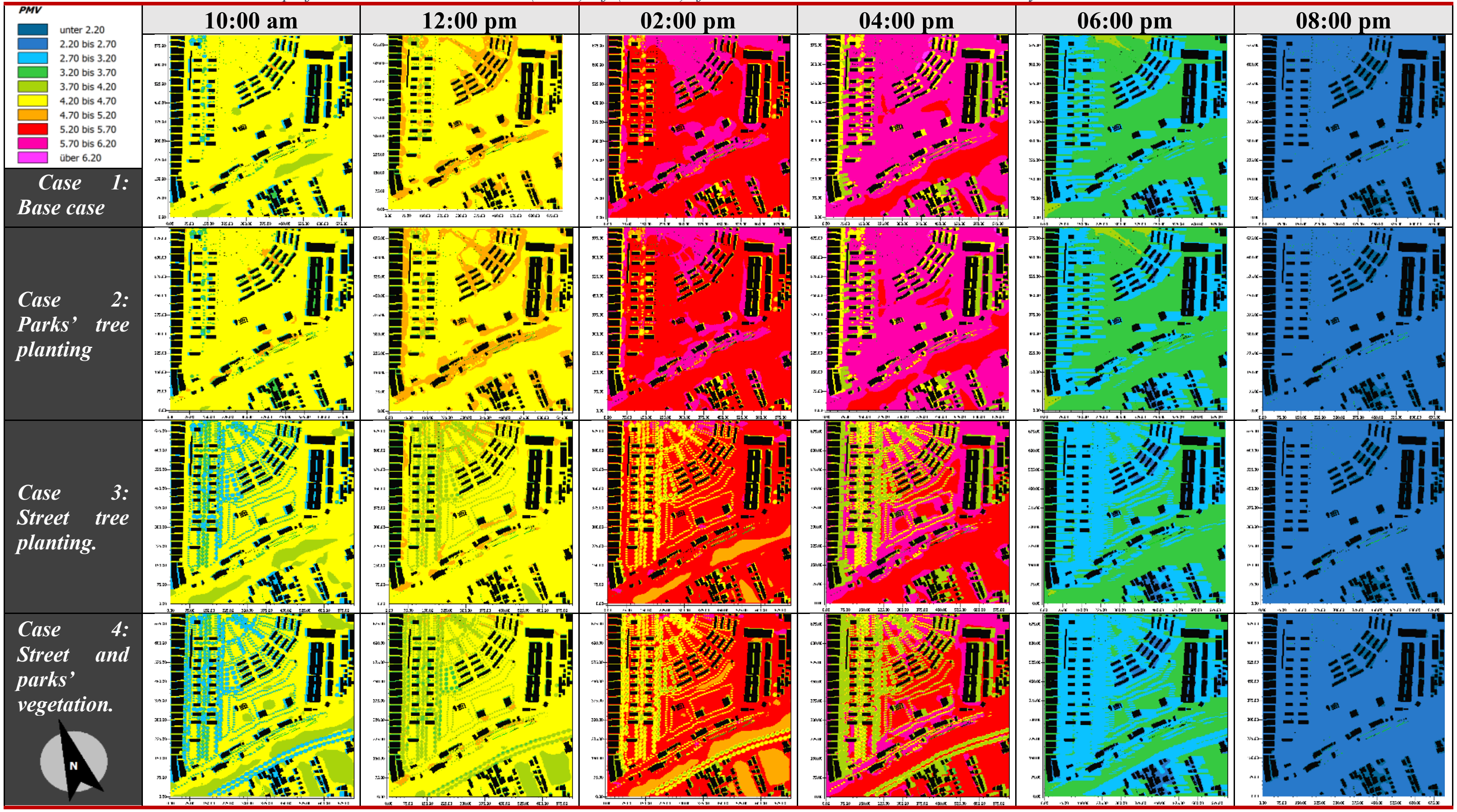
- **At 10:00 am,** compared to Case 1, Case 3 showed a 0.5-1 decrease near the river, while in Case 4 the value was 1.5-2 lower.
- **At noon,** compared to Case 1, Case 3 showed a slight decrease by 0.5, while in Case 4 the value was 0.5-1 lower.
- **At 02:00 pm,** compared to Case 1, Case 3 the value was 0.5 lower, while in Case 4 the value was 1-2 lower.
- **At 04:00 pm,** compared to Case 1, Case 3 the value was 0.5 lower, while in Case 4 the value was 1.5-2 lower.
- **At 06:00 pm,** compared to Case 1, Case 3 showed unnoticeable change, while in Case 4 the value was 0.5-1 lower.
- **At 08:00 pm,** there was no noticeable change in all cases.

- **In parks:**

The value of PMV is unnoticeably changed in Case 2 compared to case 1 all day, in cases 3 and 4:

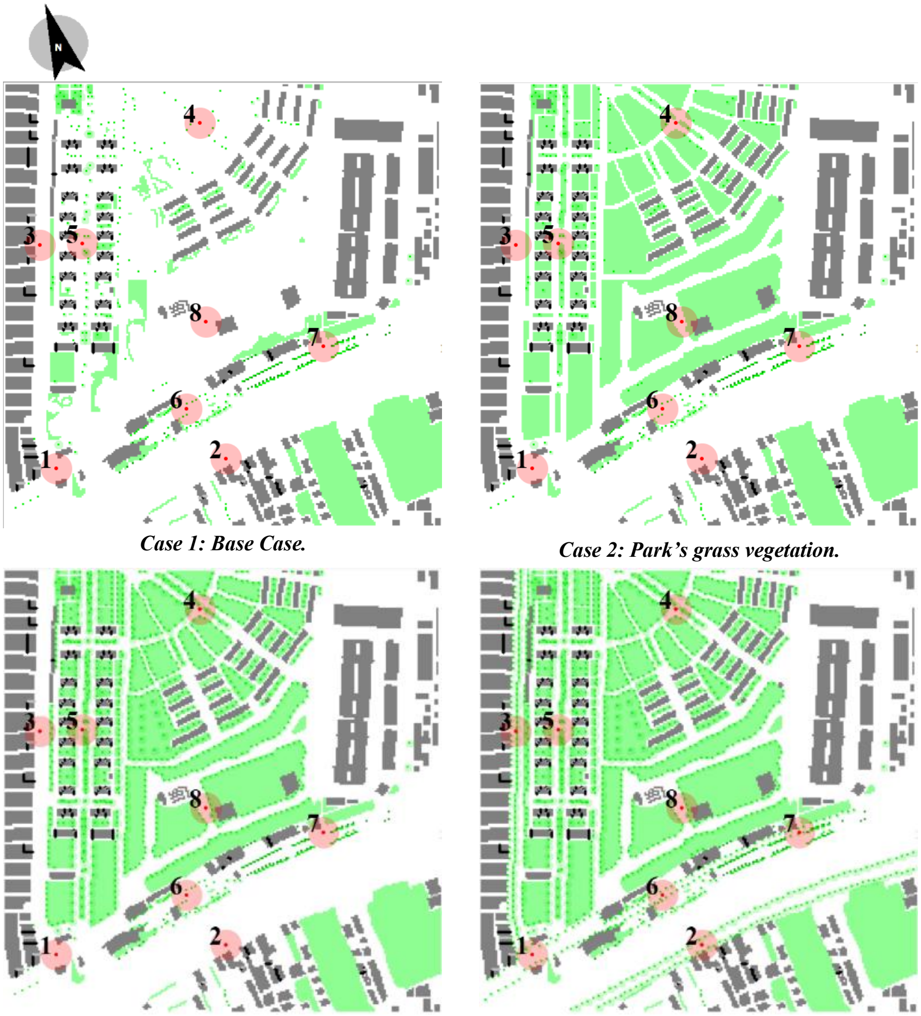
- **At 10:00 am,** Case 3 and 4 the value was 1.5-2 lower compared to Case 1.
- **At noon,** decreased by 1-1.5 compared to Case 1.
- **At 02:00 pm,** the value of PMV decreased by 1.5 compared to Case 1.
- **At 04:00 pm,** the PMV value was about 2.5 lower than Case 1.
- **At sunset hours 06:00 pm,** the PMV value was about 1 lower than Case 1.
- **At 08:00 pm,** there was no noticeable change in all cases.

Table 5-16 The Thermal Maps for Predicted Mean Vote (PMV) of (Area 2) from 10:00 Am to 08:00 Pm on 21 July 2023.



5.6.4. Receptors' Points Analysis in Study Area2

Fig. 5-9 show the measurement points location for comparison between T_{air}, Ts, MRT, and PMV in the four Cases for Area 2, in the streets, parks, the Cornish, club street and the square, the points where chosen due to its important positions in the study area, the analysis of each point is shown in Table 5-17 to Table 5-24.

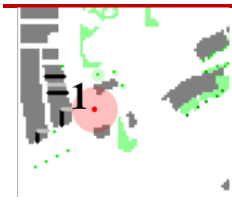


Case 1: Base Case. *Case 2: Park's grass vegetation.*

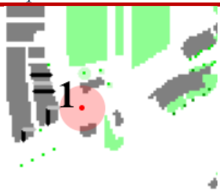
Case 3: Parks tree planting *Case 4: Street and parks' vegetation.*

Fig. 5-9 Measurement Points Location for Area 2.

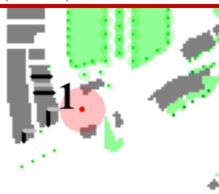
Table 5-17 Point 1 Comparison Between Tair, MRT, and PMV in Area 2.



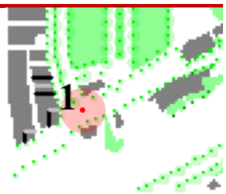
Case 1: Base Case.



Case 2: Parks grass vegetation.



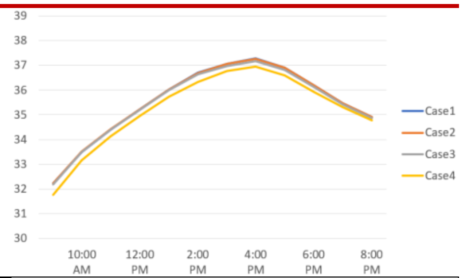
Case 3: Parks tree planting



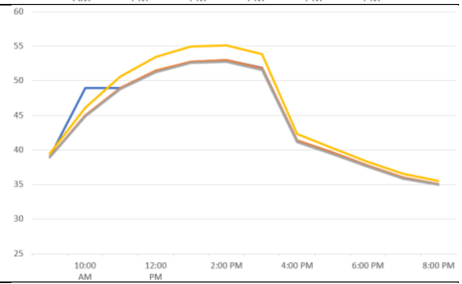
Case 4: Street and parks' vegetation.

POINT 1: Located in the street node.

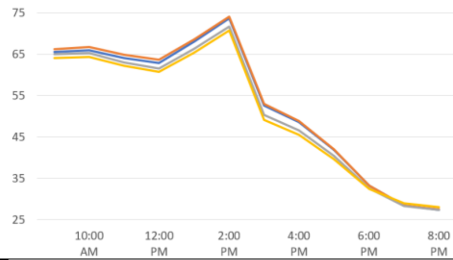
Air Temperature: the maximum rate of decrease compared to Case 1 in Case 4 reached 1% at 02:00 pm, The peak hour at 04:00 pm decreased by 0.4°C in Case 4 compared to Case 1.



Surface Temperature: the maximum rate of decrease compared to Case 1 at 10:00 am, in Case 2 reached 8.1%, while in Case 3 reached 8.4% and Case 4 reached 5.7%, The peak hours at 02:00 pm increased by 2.1°C in Case 4 compared to Case 1.



As for MRT: in Case 2 it increased by 1.3% from 10:00 am till noon, while in Case 3 the decrease reached 4.1% at 04:00 pm and in Case 4 reached 6.4% at 04:00 pm, The peak hours at 02:00 pm decreased by 3.1°C in Case 4 compared to Case 1.



As for PMV: the maximum rate of decrease compared to Case 1, in Case 3 reached 3.4% at 04:00 pm, and Case 4 reached 5.4% at 04:00 pm, The peak hours at 02:00 pm decreased by 0.2 in Case 4 compared to Case 1.

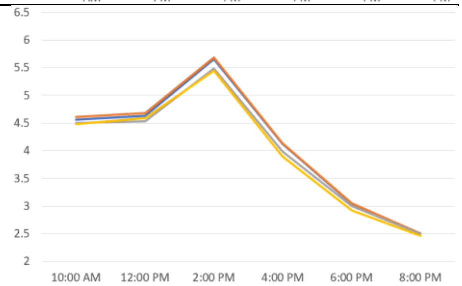
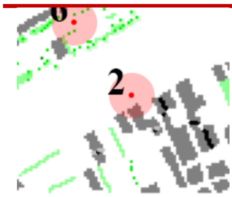
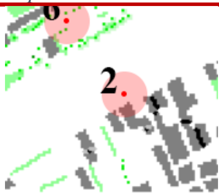


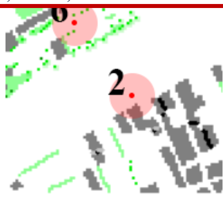
Table 5-18 Point 2 Comparison Between Tair, MRT, and PMV in Area 2.



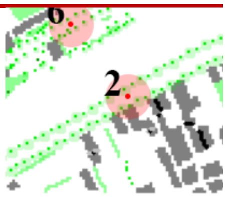
Case 1: Base Case.



Case 2: Parks grass vegetation.



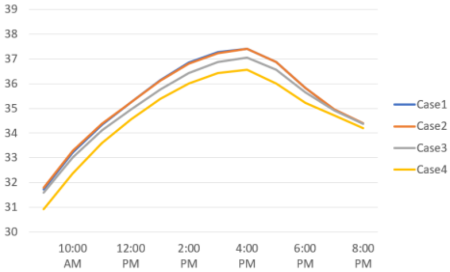
Case 3: Parks tree planting



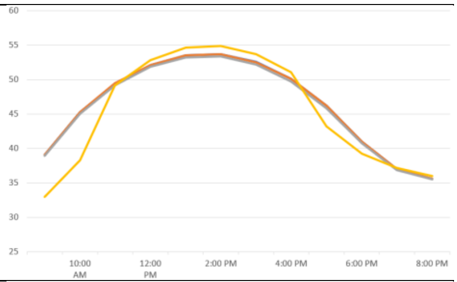
Case 4: Street and parks' vegetation.

POINT 2: Located in the middle of Cornish Street.

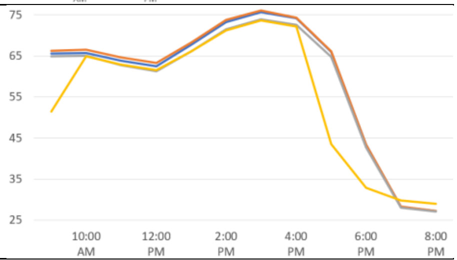
Air Temperature: the maximum rate of decrease compared to Case 1 at 02:00 pm, in Case 2 reached 0.1%, while in Case 3 the maximum rate of decrease reached 1.1%, meanwhile in Case 4 the maximum rate of decrease reached 2.3%, The peak hour 04:00 pm decreased by 0.8°C in Case 4 compared to Case 1.



Surface Temperature: the maximum rate of decrease compared to Case 1 at 02:00 pm, in Case 2 reached 0.1%, and in Case 3 reached 0.7% while Case 4 reached 15.3% at 10:00 am, The peak hours at 02:00 pm increased by 1.2°C in Case 4 compared to Case 1.



As for MRT: the maximum rate of decrease compared to Case 1, in Case 3 reached 2.4% at 02:00 pm and Case 4 reached 34.1% at 05:00 pm, The peak hours at 02:00 pm to 04:00 pm decreased by 2.1°C in Case 4 compared to Case 1.



As for PMV: the maximum rate of decrease compared to Case 1, in Case 3 reached 3.8% at 02:00 pm, and Case 4 reached 27.3% at 4:00 pm, The peak hour at 04:00 pm decreased by 1.6 in Cases 4 compared to Case 1.

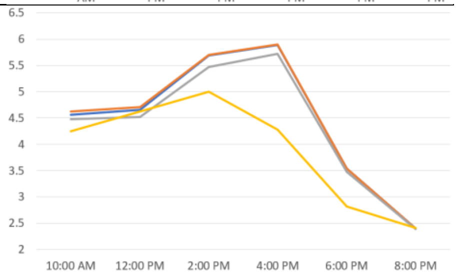
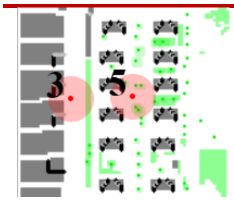
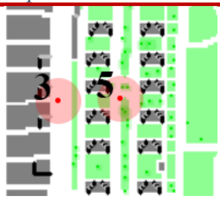


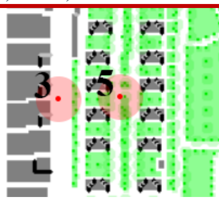
Table 5-19 Point 3 Comparison Between Tair, MRT, and PMV in Area 2.



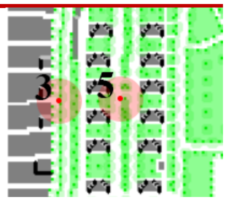
Case 1: Base Case.



Case 2: Parks grass vegetation.



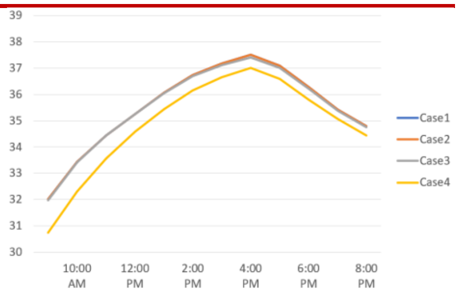
Case 3: Parks tree planting



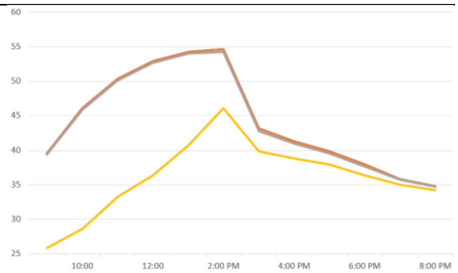
Case 4: Street and parks' vegetation.

POINT 3: Located in the middle of the street

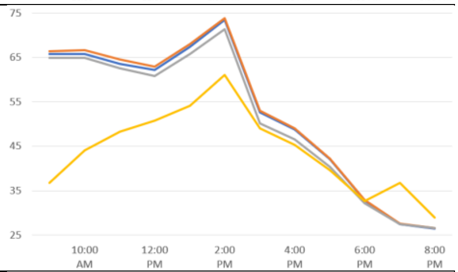
Air Temperature: the maximum rate of decrease compared to Case 1, in Case 3 the maximum rate of decrease reached 0.3% at 04:00 pm, meanwhile in Case 4 the maximum rate of decrease reached 3.4% at 10:00 am, The peak hour at 04:00 pm decreased by 0.5°C in Cases 4 compared to Case 1.



Surface Temperature: the maximum rate of decrease compared to Case 1, in Case 3 reached 0.9% at 04:00 pm while Case 4 reached 37.8% at 10:00 am, The peak hours at 02:00 pm decreased by 8.5°C in Case 4 compared to Case 1.



As for MRT: the maximum rate of decrease compared to Case 1, in Case 3 reached 4.6% at 04:00 pm and Case 4 reached 33% at 10:00 am, The peak hours at 04:00 pm decreased by 3.6°C in Case 4 compared to Case 1.



As for PMV: the maximum rate of decrease compared to Case 1, in Case 3 reached 4% at 04:00 pm, and Case 4 reached 24.3% at 04:00 pm, The peak hours at 02:00 pm decreased by 1.4 in Cases 4 compared to Case 1.

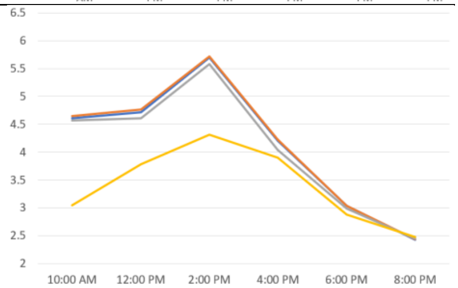
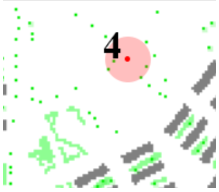


Table 5-20 Point 4 Comparison Between Tair, MRT, and PMV in Area 2.



Case 1: Base Case.

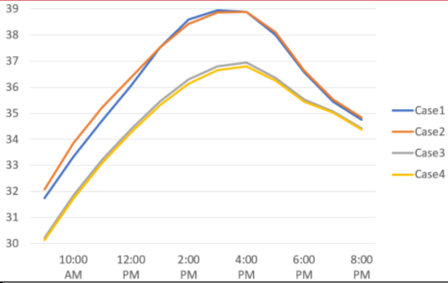
Case 2: Parks grass vegetation.

Case 3: Parks tree planting

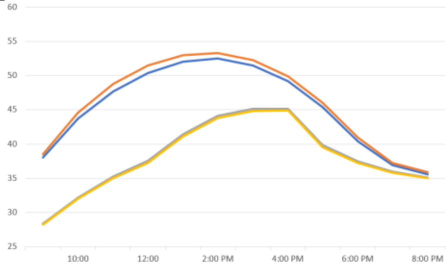
Case 4: Street and parks' vegetation.

POINT 4: Located in the middle of the residential parks.

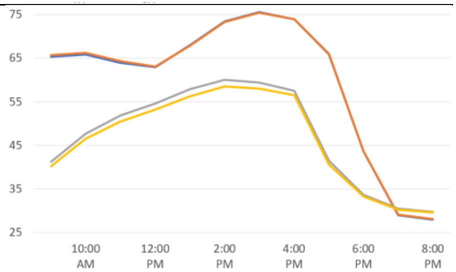
Air Temperature: the maximum rate of decrease compared to Case 1, at 02:00 pm, in Case 2 the maximum rate of decrease reached 0.4% and in Case 3 reached 6%, meanwhile in Case 4 the maximum rate of decrease reached 6.3%, The peak hour at 04:00 pm decreased by 2.1°C in Cases 4 compared to Case 1.



Surface Temperature: the maximum rate of decrease compared to Case 1, in Case 3 reached 26.3% at 10:00 am while Case 4 reached 26.8% at 10:00 am, The peak hours at 02:00 pm decreased by 8.7°C in Case 4 compared to Case 1.



As for MRT: the maximum rate of decrease compared to Case 1, in Case 2 reached 0.3% at 02:00 pm and in Case 3 reached 37% at 05:00 pm and Case 4 reached 38.4% at 05:00 pm, The peak hours at 04:00 pm decreased by 17.5°C in Case 4 compared to Case 1.



As for PMV: the maximum rate of decrease compared to Case 1, in Case 3 reached 29.8% at 04:00 pm, and Case 4 reached 31.6% at 04:00 pm, The peak hours at 04:00 pm decreased by 1.9 in Case 4 compared to Case 1.

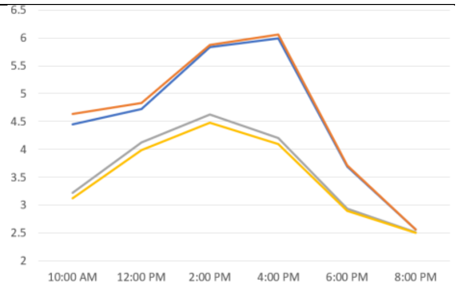
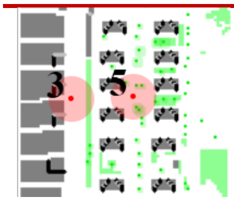
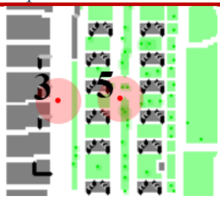


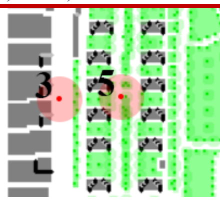
Table 5-21 Point 5 Comparison Between Tair, MRT, and PMV in Area 2.



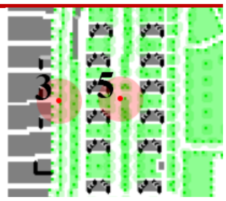
Case 1: Base Case.



Case 2: Parks grass vegetation.



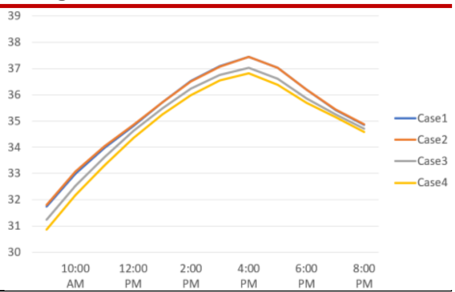
Case 3: Parks tree planting



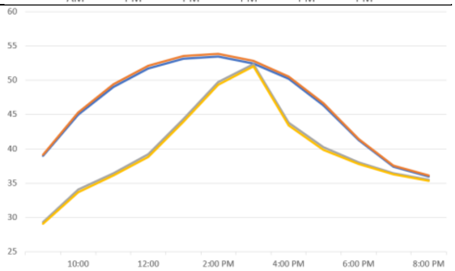
Case 4: Street and parks' vegetation.

POINT 5: Located in the residential building area.

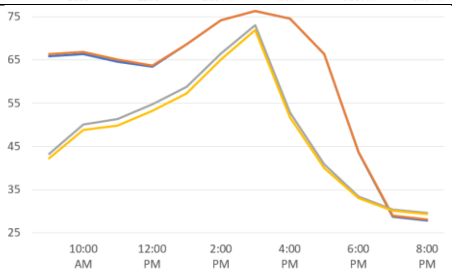
Air Temperature: the maximum rate of decrease compared to Case 1, in Case 2 reached 0.1% at 02:00 pm, while in Case 3 the maximum rate of decrease reached 1.4% at 10:00 am, meanwhile in Case 4 the maximum rate of decrease reached 2.5% at 10:00 am The peak hour 04:00 pm decreased by 0.6°C in Case 4 compared to Case 1.



Surface Temperature: the maximum rate of decrease compared to Case 1, in Case 3 reached 24.3% at 10:00 am while Case 4 reached 25% at 10:00 am, The peak hours at 02:00 pm decreased by 4.1°C in Case 4 compared to Case 1.



As for MRT: the maximum rate of decrease compared to Case 1, in Case 3 reached 38.4% at 05:00 pm and Case 4 reached 39.8% at 05:00 pm, The peak hours at 03:00 pm decreased by 4.4°C in Case 4 compared to Case 1.



As for PMV: the maximum rate of decrease compared to Case 1, in Case 2 reached 0.1% at 02:00 pm, while in Case 3 reached 24.9% at 04:00 pm, and Case 4 reached 26.8% at 04:00 am, The peak hours at 04:00 pm decreased by 1.6 in Cases 3 and 4 compared to Case 1.

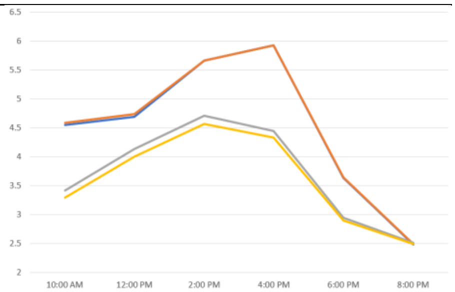
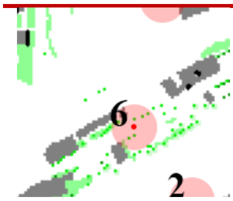
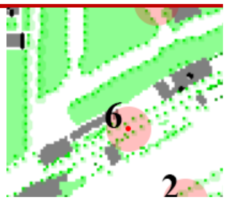


Table 5-22 Point 6 Comparison Between Tair, MRT, and PMV in Area 2.

			
Case 1: Base Case.	Case 2: Parks grass vegetation.	Case 3: Parks tree planting	Case 4: Street and parks' vegetation.

POINT 6: Located on Clubs Street.

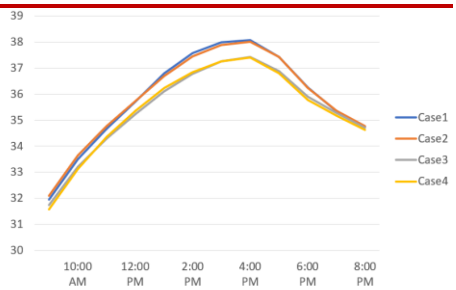
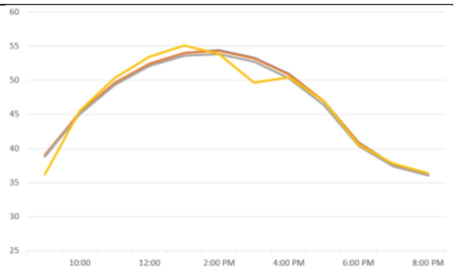
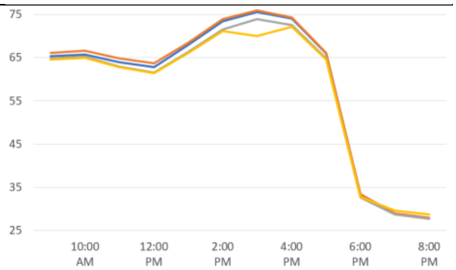
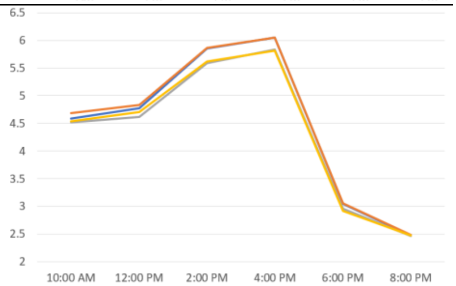
Air Temperature: the maximum rate of decrease compared to Case 1, in Case 2 reached 0.3% at 02:00 pm, while in Case 3 the maximum rate of decrease reached 2.1% at 02:00 pm, meanwhile in Case 4 the maximum rate of decrease reached 2% at 02:00 pm The peak hour 04:00 pm decreased by 0.7°C in Case 4 compared to Case 1.	
Surface Temperature: the maximum rate of decrease compared to Case 1, in Case 2 reached 0.2% at 02:00 pm, and in Case 3 reached 1.2% at 04:00 pm while Case 4 reached 6.8% at 03:00 pm, The peak hours at 02:00 pm decreased by 0.5°C in Case 4 compared to Case 1.	
As for MRT: the maximum rate of decrease compared to Case 1, in Case 3 reached 2.5% at 02:00 pm and Case 4 reached 7.5% at 03:00 pm, The peak hours at 03:00 pm decreased by 2.5°C in Case 4 compared to Case 1.	
As for PMV: the maximum rate of decrease compared to Case 1, in Case 3 reached 4.6% at 02:00 pm, and Case 4 reached 4.3% at 06:00 pm, The peak hours at 04:00 pm decreased by 0.2 in Case 4 compared to Case 1.	

Table 5-23 Point 7 Comparison Between Tair, MRT, and PMV in Area 2.

Case 1: Base Case.

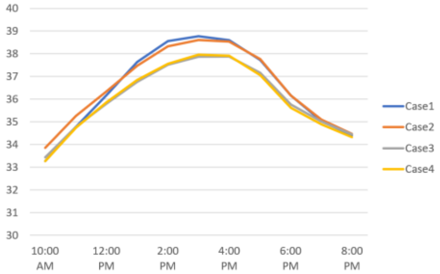
Case 2: Parks grass vegetation.

Case 3: Parks tree planting

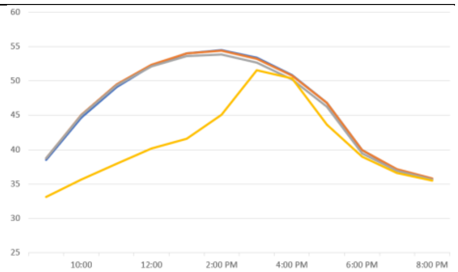
Case 4: Street and parks' vegetation.

POINT 7: Located on Club Street.

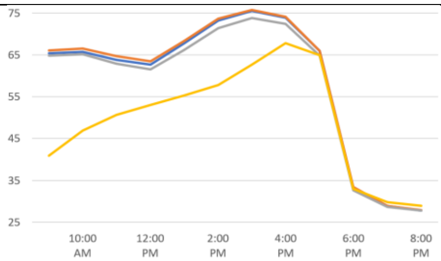
Air Temperature: the maximum rate of decrease compared to Case 1, at 02:00 pm, in Case 2 reached 0.6%, and in Case 3 the maximum rate of decrease reached 2.7%, meanwhile in Case 4 the maximum rate of decrease reached 2.6%, The peak hour 04:00 pm decreased by 0.7°C in Case 3 and 4 compared to Case 1.



Surface Temperature: the maximum rate of decrease compared to Case 1, in Case 2 reached 0.2% at 02:00 pm, and in Case 3 reached 1.3% at 04:00 pm while Case 4 reached 23% at noon, The peak hours at 02:00 pm decreased by 9.4°C in Case 4 compared to Case 1.



As for MRT: the maximum rate of decrease compared to Case 1, in Case 3 reached 2.5% at 02:00 pm and Case 4 reached 21.1% at 02:00 pm, The peak hours at 03:00 pm decreased by 12.8°C in Case 4 compared to Case 1.



As for PMV: the maximum rate of decrease compared to Case 1, in Case 2 reached 0.1% at 02:00 pm, while in Case 3 reached 5% at 02:00 am, and Case 4 reached 4.6% at 06:00 pm, The peak hours at 04:00 pm decreased by 0.2 in Case 4 compared to Case 1.

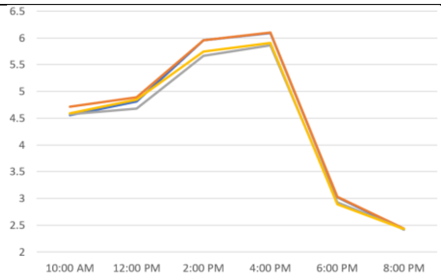
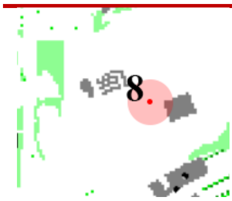


Table 5-24 Point 8 Comparison Between Tair, MRT, and PMV in Area 2.



Case 1: Base Case.

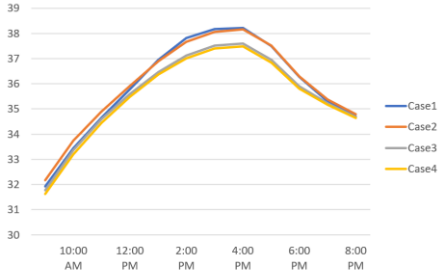
Case 2: Parks grass vegetation.

Case 3: Parks tree planting

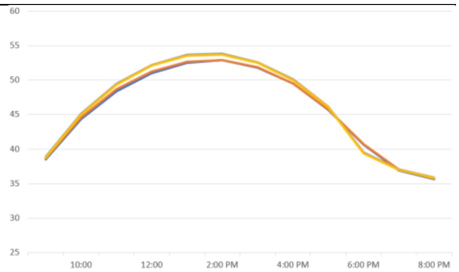
Case 4: Street and parks' vegetation.

POINT 8: Located in the middle of industrial area.

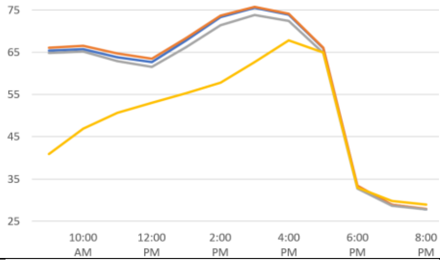
Air Temperature: the maximum rate of decrease compared to Case 1, in Case 2 reached 0.4% at 02:00 pm, while in Case 3 the maximum rate of decrease reached 1.9% at 02:00 pm, meanwhile in Case 4 the maximum rate of decrease reached 2.1% at 02:00 pm The peak hour 04:00 pm decreased by 0.7°C in Case 4 compared to Case 1.



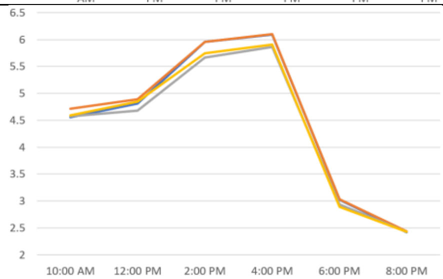
Surface Temperature: the maximum rate of decrease compared to Case 1, in Case 3 reached 2.8% at 06:00 pm while Case 4 reached 3.1% at 06:00 pm, The peak hours at 02:00 pm increased by 0.8°C in Case 4 compared to Case 1.



As for MRT: the maximum rate of decrease compared to Case 1, in Case 2 reached 0.3% at 02:00, while in Case 3 reached 22.7% at 06:00 pm and Case 4 reached 23.5% at 06:00 pm, The peak hours at 03:00 pm decreased by 2.8°C in Case 4 compared to Case 1.



As for PMV: the maximum rate of decrease compared to Case 1, in Case 2 reached 0.6% at 02:00 pm, while in Case 3 reached 17% at 06:00 pm, and Case 4 reached 17.9% at 06:00 pm, The peak hours at 04:00 pm decreased by 0.2 in Case 4 compared to Case 1.



Adding grass only decreased the surface temperature while it showed an unnoticeable decrease in air temperature, adding trees in the residential park area improved thermal performance. However, adding trees in streets and parks has the most optimal thermal performance in the entire area between the four cases.

5.7. Study Area3

The area is located in the south of El-Mahalla El-Kubra city, the area's main axis is a main road on the side of a railway line and the cross axis is a large park and clubs, surrounded by El-Mahalla Chest Hospital, a school, and a group of dense residential blocks, the area was chosen as it is a dense area in the city, it has one of the main parks in the city and public facilities that can be redesigned (Fig. 5-10).

Fig. 5-10 Study Area3, El-Mahalla El-Kubra city. (Source: Google earth, Author 2024)

5.7.1. Study Area3 Simulation Scenarios Description

Three scenarios are proposed to assess the effectiveness of the proposed UGI principles in defining the air temperature and mean radiant temperature (MRT) of the simulation model. All scenarios are modelled in ENVI-met 4.0 applications (Fig. 5-11). Consider the elements used in the analytical study of the same climate region in each scenario.

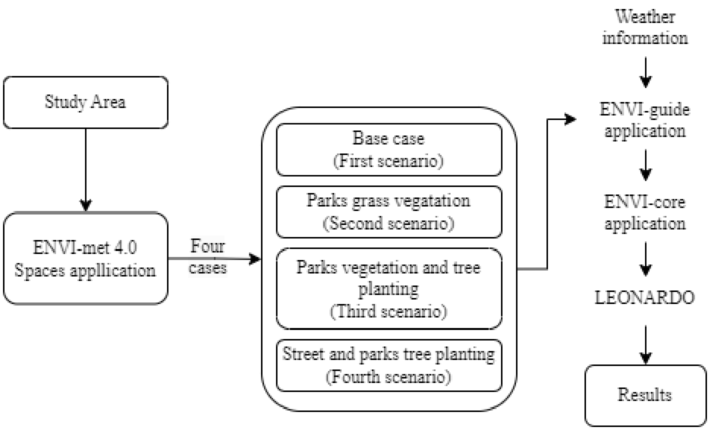


Fig. 5-11 Simulation Description of Assessment of the Effectiveness of UGI in Study Area3. (Source: Author)

a. Case 1: Base Case for Area 3:

Refers to the base case of the study area. All related features, whether planted or built, are added as they are in the real world. The percentage of green coverage is 6% (Fig. 5-8, a).

b. Case 2: The First Scenario for Area 3 (Grass):

Involves tree planting on existing surfaces, the percentage of green coverage is 14%. This scenario includes the following measures (Fig. 5-8, b):

- Design parks with dense grass in the residential neighborhood.
- Adding dense grass to the hospital area vacant land and the park.

c. Case 3: The Second Scenario for Area 3 (Parks Vegetation and Tree Planting):

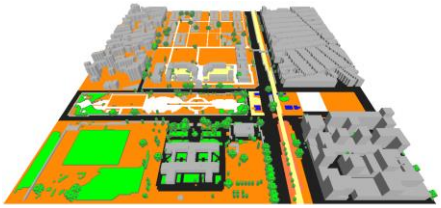
Involves tree planting on existing surfaces, the percentage of green coverage is 15%. This scenario includes the following measures (Fig. 8, c):

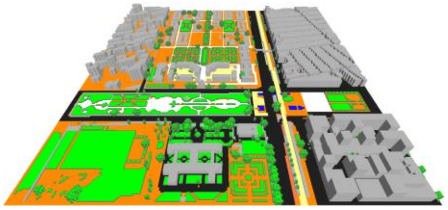
- Adding dense grass and large canopy trees to the park.
- Vacant lands are converted to the neighborhoods’ parks by adding dense grass and trees.
- Add dense grass to the existing playgrounds and a line of large canopy trees surrounding them.
- Adding dense grass and trees to the hospital's vacant land.

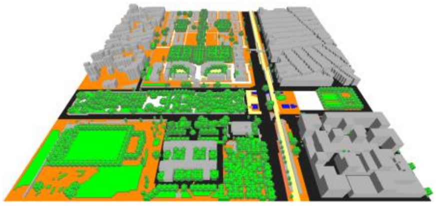
d. Case 4: The Third Scenario for Area 3 (Street and Parks Tree Planting):

Following the green infrastructure principles, which involve greening the existing surfaces, the percentage of green coverage is 25%. This scenario includes the following measures (Fig. 5-8, d):

- Tiled and soiled spaces in the middle and next to streets by adding large canopy trees and high-density grass.
- Adding large canopy trees and high-density grass on the sides of the railroad bank.
- Adding trees to the residential blocks’ streets.


Case 1: Base case.


Case 2: Parks grass vegetation.


Case 3: Parks tree planting and vegetation.

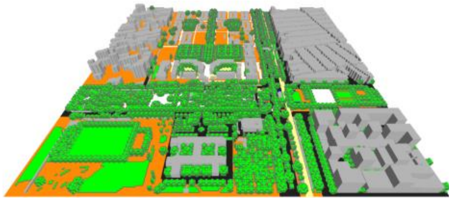

Case 4: Street and parks vegetation.

Fig. 5-12 The Four Cases for Area 3.

5.7.2. Area3 Simulation Settings

The model has an area of about 0.49km2 with the dimensions 700*700m2. Buildings' average height ranges between 4 to 36 m, and the dimensions of the simulation grid for the model domain are 717 (x) * 717 (y)* 75 (z)m. The number of cells at each axis is 239*239*25, while the cell size is 3*3*3m respectively. Model north rotation is 37.7˚, air temperature is 28-39°C, relative humidity is 50-70%, wind speed at the inflow border is 3m/s and the wind direction (constant wind direction at inflow) is 320°. The trees used in the ENVI-met program are represented in Table 5-1.

Table 5-25 The Used Trees in the ENVI-met Program.

Used trees	Height (m)	Crown Width (m)
Cassia Leptophylla	12	7
Koelreuteria Paniculata	10	13
Betula Pendula	6	7
Palm Washingtonia	20	3
Senegalia Greggii	2	3

5.7.3. Area 3 Simulation Results

By simulation the three cases from 10:00 am to 08:00 pm on Summer, 21 July 2023, the following tables show; the air temperature (Ta), mean radiant temperature (MRT) and predicted mean vote (PMV) to identify the thermal comfort.

a. Air Temperature (Tair)

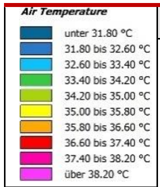
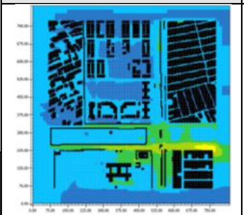
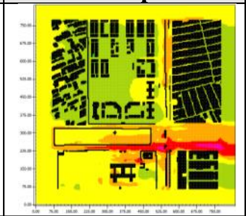
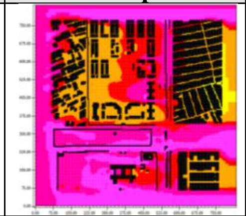
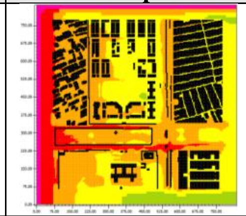
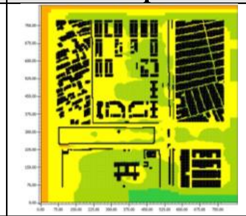
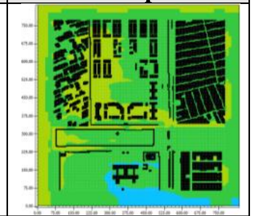
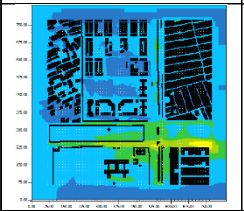
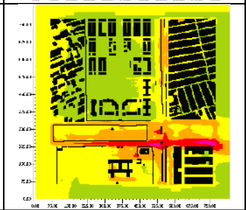
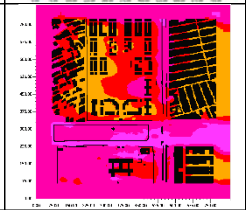
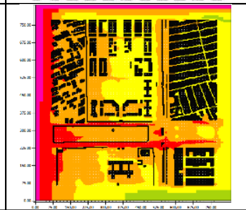
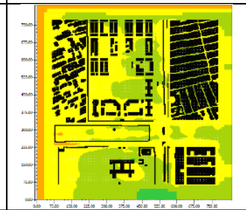
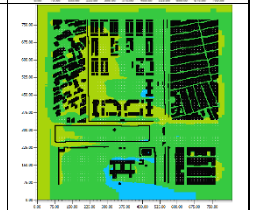
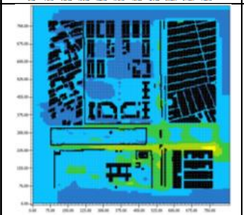
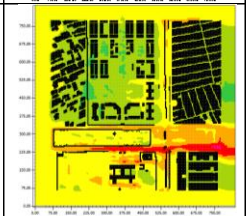
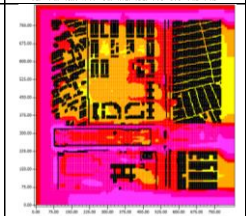
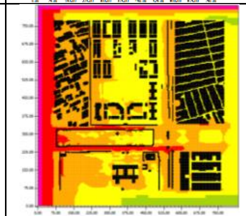
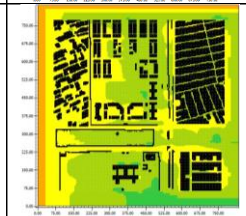
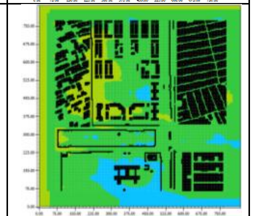
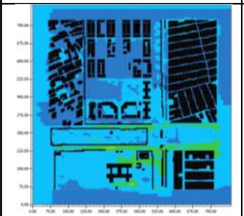
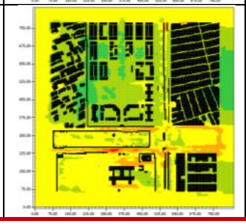
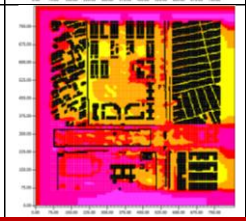
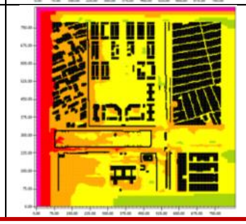
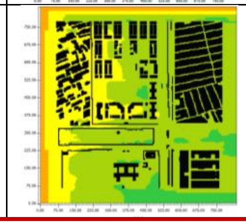
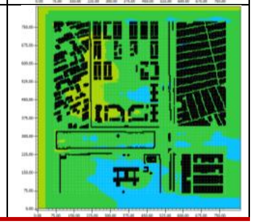
By analyzing the air temperature from 10:00 am to 08:00 pm (Table 5-26), the following was found:

The air temperature showed an unnoticeable change in Case 2 compared to Case 1 the current situation. In Case 3 the was an unnoticeable change in the streets compared to Case 1. Meanwhile, it decreased significantly in the parks, in Case 4 the air temperature decreased in the entire area.

- **In streets:**
  - **At 10:00 am,** Case 3 showed no significant change compared to Case 1, while in Case 4, it decreased by 0.8°C.
  - **At noon,** Case 3 decreased by 0.8-1.6°C compared to Case 1, while in Case 4, it decreased by 1.6-2.4°C.
  - **At 02:00 pm,** Case 3 decreased by 0.8-1.6°C, and in Case 4 the Ta decreased by 1.6-2.4°C compared to Case 1.
  - **At 04:00 and 06:00 pm,** the Tair unnoticeable change in Case 3, while in Case 4 the Ta decreased by 0.8-1.6°C compared to Case 1.
  - **At 08:00 pm,** Cases 3 and 4 showed an unnoticeable change in the street.

- **In parks:**
  - **At 10:00 am,** Case 3 showed no significant change compared to Case 1, while in Case 4, it decreased by 0.8°C.
  - **At noon,** Case 3 decreased by 0.8-1.6°C compared to Case 1, while in Case 4, it decreased by 0.8-1.6°C.
  - **At 02:00 pm,** Case 3 decreased by 0.8-2.4°C, and in Case 4 the Ta decreased by 1.6-2.4°C compared to Case 1.
  - **At 04:00 and 06:00 pm,** Cases 3 and 4 decreased by 0.8-1.6°C compared to Case 1.
  - **At 08:00 pm,** Cases 3 and 4 decreased by 0.8°C in the parks area.

Table 5-26 The Thermal Maps for Tair of (Area 3) from 10:00 Am to 08:00 Pm on 21 July 2023.

	10:00 am	12:00 pm	02:00 pm	04:00 pm	06:00 pm	08:00 pm
Case 1: Base case						
Case 2: Parks grass vegetation						
Case 3: Parks tree planting.						
Case 4: Street and parks' vegetation. 						

b. Surface temperature (Ts)

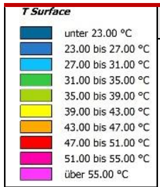
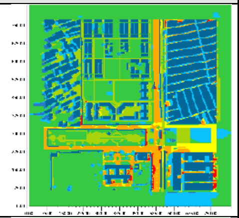
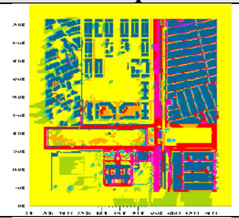
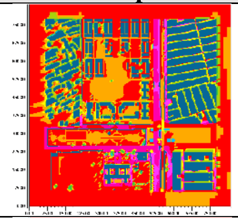
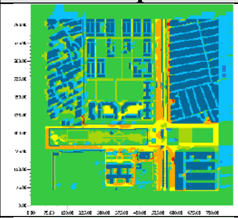
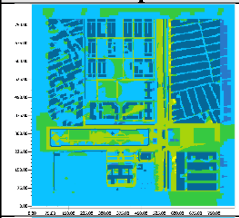
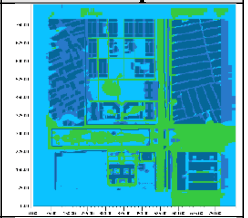
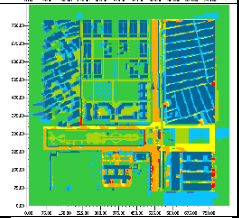
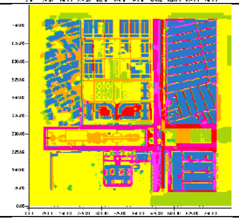
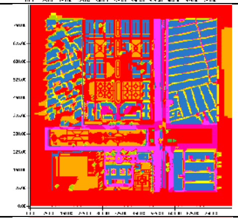
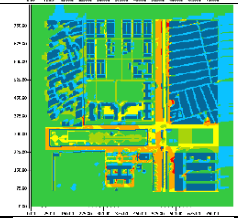
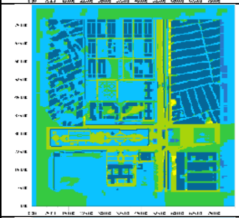
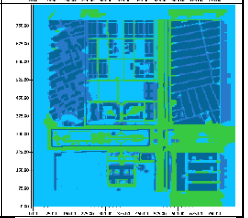
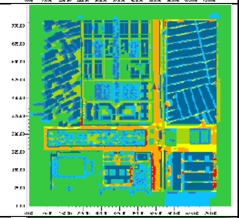
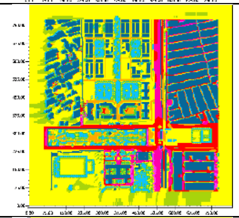
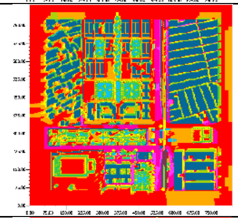
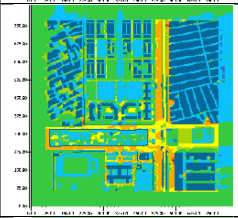
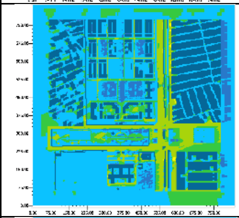
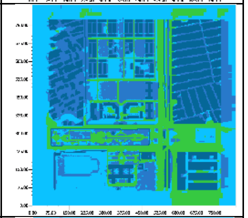
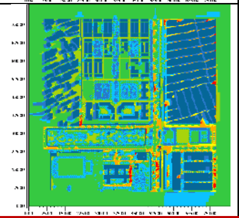
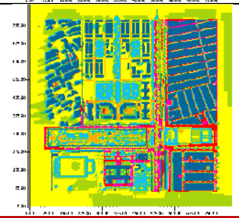
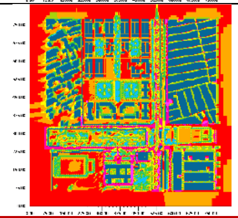
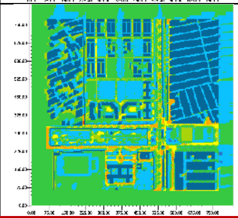
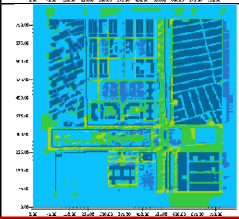
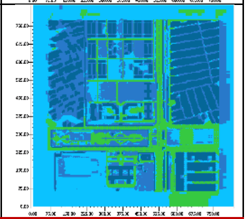
By analyzing the surface temperature (Ts) from 10:00 am to 08:00 pm (Table 5-27), the following was found:

The surface temperature showed an unnoticeable change in Case 2 compared to Case 1 in streets and showed a slight decrease in parks area. In Case 3 the was an unnoticeable change in the streets. Meanwhile, it decreased significantly in the parks. Case 4 the surface temperature decreased in the streets and parks area.

- **In streets:**
  - **At 10:00 am,** Cases 2 and 3 compared to Case 1 showed unnoticeable change, while in Case 4 it decreased by 16-20°C.
  - **At noon**, Cases 2 and 3 showed unnoticeable change compared to Case 1, while in Case 4 it decreased by 16-20°C.
  - **At 02:00 pm**, Cases 2 and 3 showed unnoticeable change compared to Case 1, while in Case 4 it decreased by 12-16°C.
  - **At 04:00 pm,** Cases 2 and 3 showed unnoticeable change compared to Case 1, while in Case 4 it decreased by 8-12°C.
  - **At 06:00 pm,** Cases 2 and 3 showed unnoticeable change compared to Case 1, while in Case 4 it decreased by 4°C.
  - **At 08:00 pm,** the three cases showed an unnoticeable change in the streets.

- **In parks:**
  - **At 10:00 am,** compared to Case 1, Case 2 slightly decreased by 4°C, and Cases 3 and 4 decreased by 4-12°C.
  - **At noon**, compared to Case 1, Case 2 slightly decreased by 4°C, and Cases 3 and 4 decreased by 12-16°C.
  - **At 02:00 pm**, compared to Case 1, Case 2 slightly decreased by 4°C, and Cases 3 and 4 decreased by 16-20°C.
  - **At 04:00 and 06:00 pm,** compared to Case 1, Case 2 showed unnoticeable change, and Cases 3 and 4 decreased by 4-8°C.
  - **At 08:00 pm, ,** compared to Case 1, Case 2 slightly decreased about 4°C, and Cases 3 and 4 decreased by 4-8°C.

Table 5-27 The Thermal Maps for Surface Temperature of (Area 3) from 10:00 Am to 08:00 Pm on 21 July 2023.

	**10:00 am**	**12:00 pm**	**02:00 pm**	**04:00 pm**	**06:00 pm**	**08:00 pm**
Case 1: Base case						
Case 2: Parks grass vegetation						
Case 3: Parks tree planting.						
Case 4: Street and parks' vegetation. 						

c. Mean Radiant Temperature (MRT)

By analyzing the MRT from 10:00 am to 08:00 pm (Table 5-28), the following was found:

In Case 2, parks showed a slight temperature decrease in the early morning, while streets showed unnoticeable change. Case 3 showed a noticeable temperature drop in parks but no significant change in streets. In contrast, Case 4 exhibited a significant temperature decrease across the entire area.

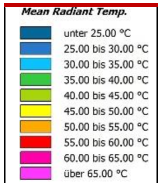
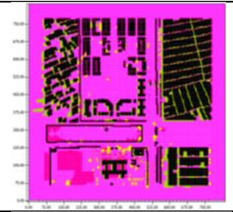
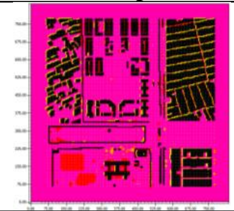
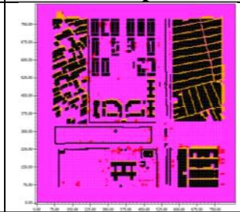
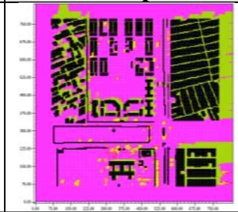
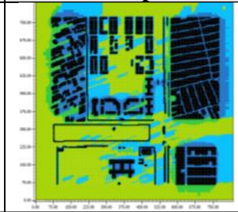
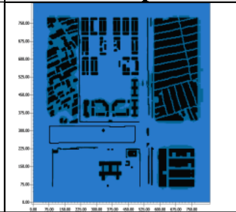
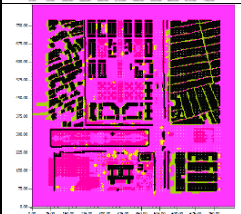
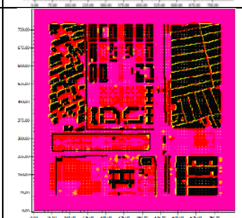
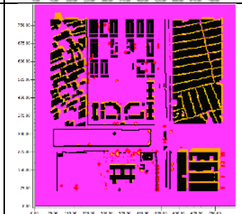
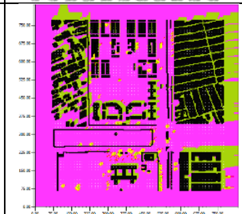
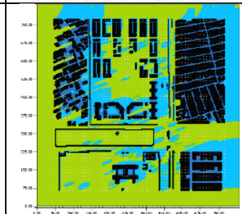
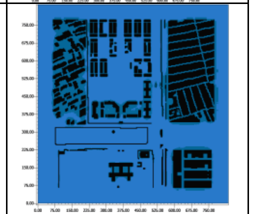
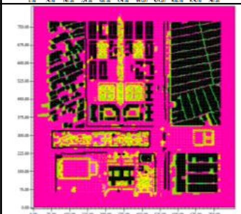
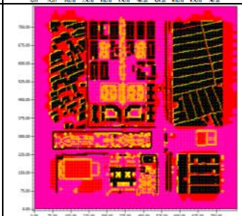
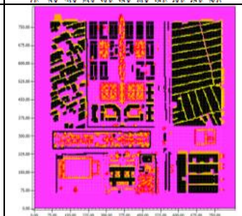
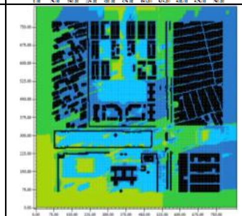
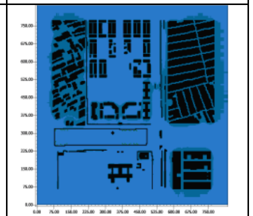
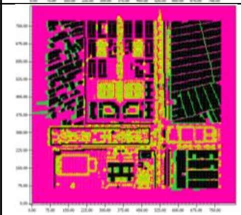
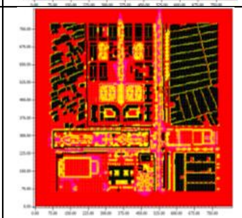
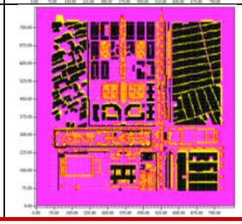
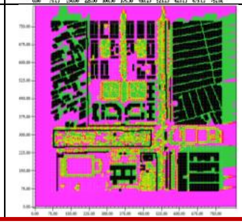
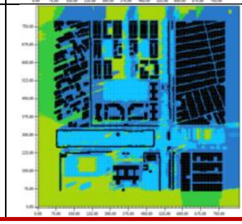
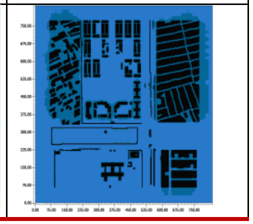
- **In streets:**

Compared to Case 1, Case 2 shows an unnoticeable change, while Cases 3 and 4:

- **At 10:00 am,** compared to Case 1, Case 3 decreased by 5°C, and Case 4 decreased by 5-25°C.
- **At noon,** compared to Case 1, Cases 2 and 3 show unnoticeable changes, and Case 4 decreased by 5-15°C.
- **At 02:00 pm,** compared to Case 1, Case 3 showed unnoticeable change, and Case 4 decreased by 5-10°C.
- **At 04:00 pm,** compared to Case 1, Case 3 showed unnoticeable change, and Case 4 decreased by about 25-30°C.
- **At sunset hours 06:00 pm,** compared to Case 1, Case 3 decreased by 5°C. Meanwhile, in Case 4, it decreased by 10-15°C.
- **At 08:00 pm,** showed an unnoticeable change.

- **In parks:**
  - **At 10:00 am,** compared to Case 1, Case 2 decreased by 5°C, Case 3 decreased by 20-25°C and Case 4 decreased by 5-25°C.
  - **At noon,** compared to Case 1, Case 2 decreased by 5°C, while Case 3 decreased by 10-15°C, Case 4 decreased by 20°C.
  - **At 02:00 pm,** Case 2 showed unnoticeable change compared to Case 1, Case 3 and 4 decreased by 5-10°C.
  - **At 04:00 pm,** Case 2 showed unnoticeable change in the entire area compared to Case 1, Case 3 decreased by 25°C and Case 4 decreased by 25-30°C.
  - **At sunset hours 06:00 pm,** Case 2 showed an unnoticeable change compared to Case 1, Case 3 decreased by 10-15°C. Meanwhile, in Case 4, it decreased by 10-15°C.
  - **At 08:00 pm,** showed unnoticeable in the three cases.

Table 5-28 The Thermal Maps for Mean Radiant Temperature of (Area 3) from 10:00 Am to 06:00 Pm on 21 July 2023.

	10:00 am	12:00 pm	02:00 pm	04:00 pm	06:00 pm	08:00 pm
Case 1: Base case						
Case 2: Parks grass vegetation						
Case 3: Street tree planting.						
Case 4: Street and parks' vegetation.						

d. Predicted Mean Vote (PMV)

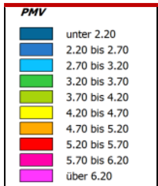
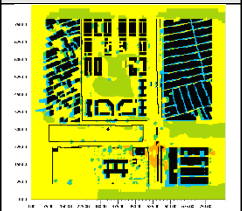
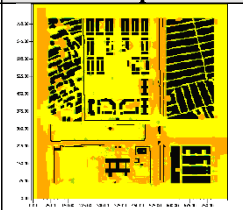
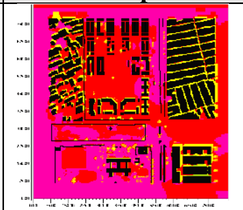
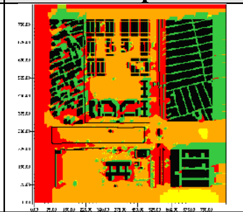
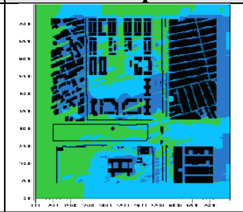
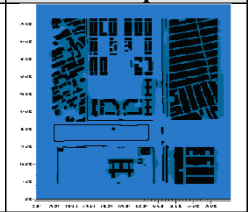
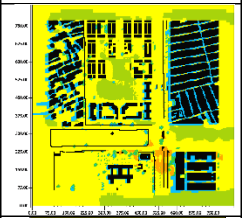
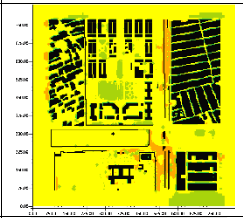
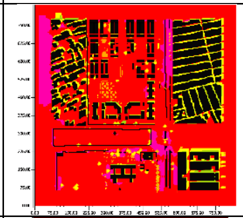
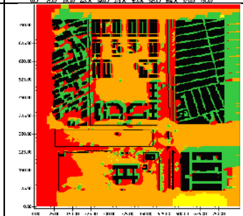
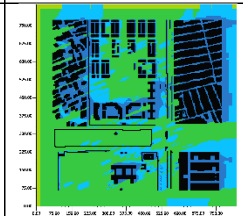
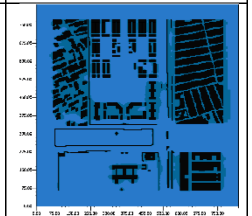
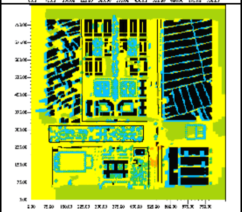
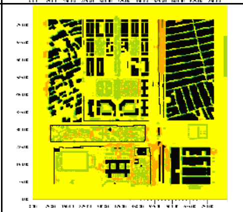
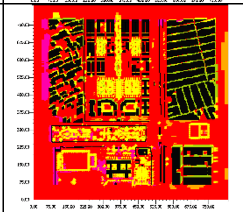
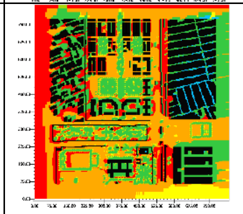
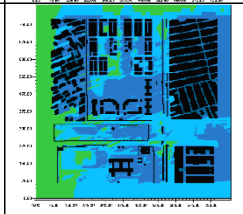
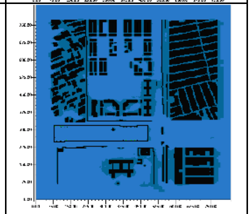
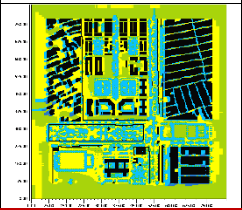
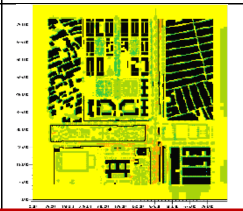
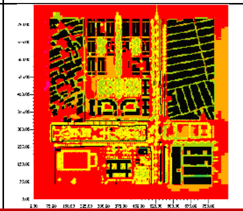
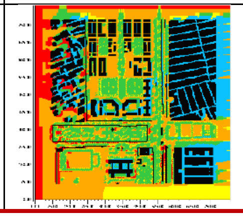
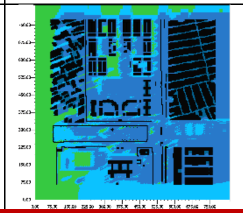
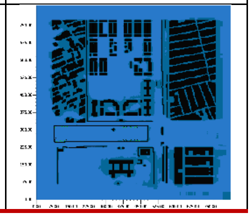
By analyzing the predicted mean vote (PMV) in study area 1 to identify the thermal comfort from 10:00 am to 08:00 pm (Table 5-29), the following was found:

The value of PMV case 2 showed unnoticeable change compared to Case 1, Case 3 decreased significantly in the parks while in the streets it slightly decreased. Meanwhile, in Case 4, it decreased significantly in the entire area.

- **In streets:**
  - **At 10:00 am**, Case 3 showed an unnoticeable change compared to Case 1, while in Case 4 the value was 1.5-2 lower.
  - **At noon,** Case 3 compared to Case 1 was about 00.5-1 lower, while in Case 4 it decreased by 1-1.5.
  - **At 02:00 p.m.,** Cases 2 and 3 had decreased about 0.5-1 compared to Case 1, and Case 4 had significantly decreased by 1.5-2.
  - **At 04:00 pm,** Case 3 in the streets showed an unnoticeable change compared to Case 1, while Case 4 was about 2-2.5 lower.
  - **At sunset hours 06:00 pm,** Case 3 compared to Case 1 was about 0.5 lower, while Case 4 was about 1-1.5 lower.
  - **At 08:00 pm,** showed unnoticeable in the three cases.

- **In parks:**
  - **At 10:00 am,** compared to Case 1, Case 3 was 1-1.5 lower while in Case 4 the value was 1-2 lower.
  - **At noon,** compared to Case 1, Case 3 was about 0.5 lower, while in Case 4 it decreased by 1-1.5.
  - **At 02:00 p.m.,** compared to Case 1, Case 3 decreased in parks about 1-1.5 and Case 4 had significantly decreased by 1.5-2.
  - **At 04:00 pm,** compared to Case 1, Case 3 decreased about 1.5-2, Case 4 1-1.5 lower.
  - **At sunset hours 06:00 pm,** compared to Case 1, Case 3 was about 0.5-1 lower, while Case 4 was about 0.5-1 lower.
  - **At 08:00 pm,** showed unnoticeable in the three cases.

Table 5-29 The Thermal Maps for Predicted Mean Vote (PMV) of (Area 3) from 10:00 Am to 08:00 Pm on 21 July 2023

	**10:00 am**	**12:00 pm**	**02:00 pm**	**04:00 pm**	**06:00 pm**	**08:00 pm**
Case 1: Base case						
Case 2: Parks grass vegetation						
Case 3: Street tree planting.						
Case 4: Street and parks' vegetation. 						

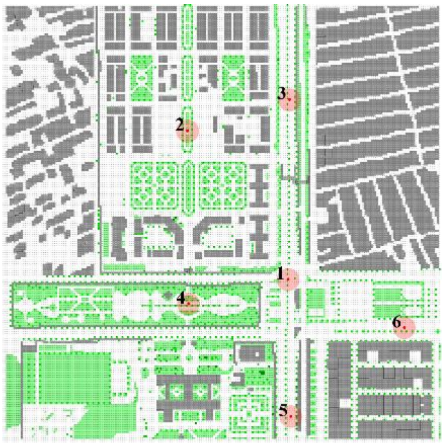
5.7.4. Receptors' Points Analysis in Study Area 3

Fig. 5-13 show the measurement points location for comparison between T_{air}, MRT, and PMV in the four Cases for Area 1, in the middle of the streets, street nodes and the parks, the points where chosen due to its important positions in the study area, the analysis of each point is shown in (Table 5-30 - Table 5-35)

Case 1: Base Case.

Case 2: Parks grass vegetation.

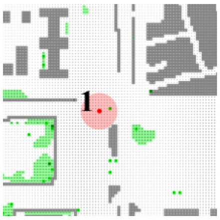
Case 3: Parks tree planting



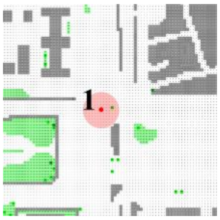
Case 4: Street and parks' vegetation.

Fig. 5-13 Measurement Points Location for Area 3.

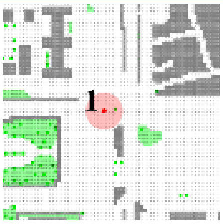
Table 5-30 Point 1 Comparison Between Tair, MRT, and PMV in Area 3.



Case 1: Base Case.



Case 2: Parks grass vegetation.

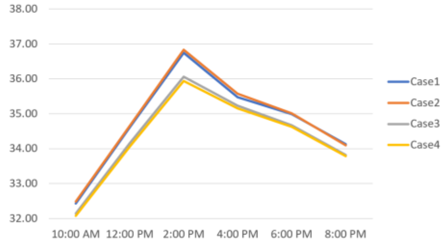


Case 3: Parks tree planting

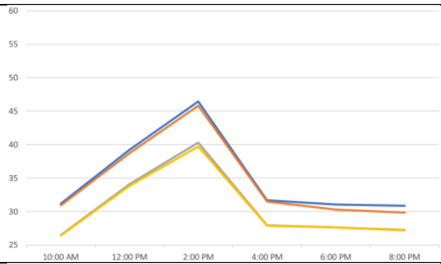
Case 4: Street and parks' vegetation.

POINT 1: Located in the road node

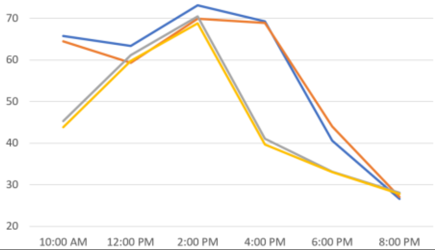
Air Temperature: the maximum rate of decrease compared to Case 1, in Case 2 reached 0.1% at 08:00 pm, while in Case 3, it reached 1.9 % at 02:00 pm. In comparison, in Case 4 reached 2.2% at 02:00 pm, The peak hour at 02:00 pm decreased by 0.8°C in Case 4 compared to Case 1.



Surface Temperature: the maximum rate of decrease compared to Case 1 at 02:00 pm, in Case 2 reached 1.4%, in Case 3 reached 13.3% while Case 4 reached 14.5%, The peak hours at 02:00 pm decreased by 6.8°C in Case 4 compared to Case 1.



As for MRT: the maximum rate of decrease compared to Case 1, in Case 2 reached 6.4% at noon, while in Case 3 reached 40.7% at 04:00 pm and Case 4 reached 42.7% at 04:00 pm, The peak hours at 02:00 pm decreased by 4.3°C in Case 4 compared to Case 1.



As for PMV: the maximum rate of decrease compared to Case 1, in Case 2 reached 7.4% at noon, while in Case 3 reached 32.3% at 04:00 pm, and Case 4 reached 34.1% at 04:00 am, The peak hours at 02:00 pm decreased by 0.3 in Case 4 compared to Case 1.

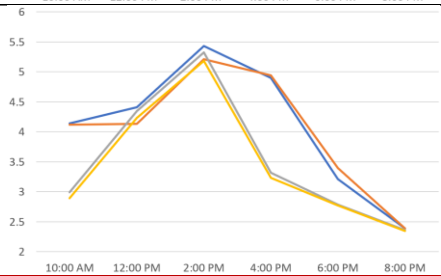
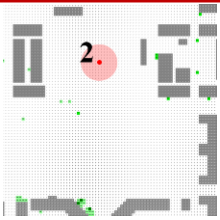
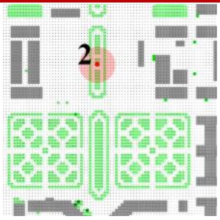


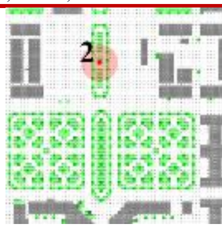
Table 5-31 Point 2 Comparison Between Tair, MRT, and PMV in Area 3.



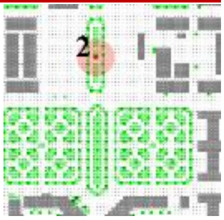
Case 1: Base Case.



Case 2: Parks grass vegetation.



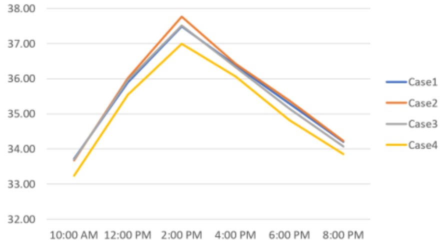
Case 3: Parks tree planting



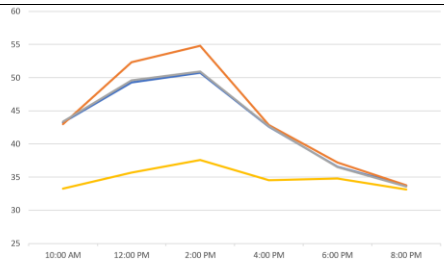
Case 4: Street and parks' vegetation.

POINT 2: Located in the middle of the residential buildings' parks

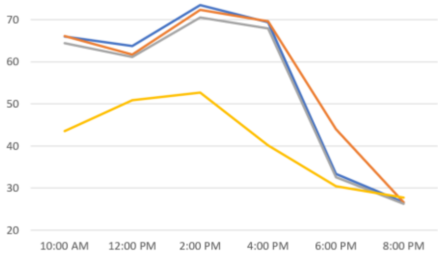
Air Temperature: the maximum rate of decrease compared to Case 1, in case 2 reached 0.1% at 10:00 am, while in Case 3 reached 0.4% at 06:00 pm. In comparison, Case 4 reached 1.3% at 02:00 pm and 06:00 pm, The peak hour at 02:00 pm decreased by 0.5°C in Case 4 compared to Case 1.



Surface Temperature: the maximum rate of decrease compared to Case 1, in Case 2 reached 0.6% at 10:00 am, in Case 3 reached 0.3% at 08:00 pm while Case 4 reached 27.6% at noon, The peak hours at 02:00 pm decreased by 13.1°C in Case 4 compared to Case 1.



As for MRT: the maximum rate of decrease compared to Case 1, in Case 2 reached 3.2% at noon, while in Case 3 reached 4.1% at noon and Case 4 reached 42.1% at 04:00 pm, The peak hours at 02:00 pm decreased by 20.8°C in Case 4 compared to Case 1.



As for PMV: the maximum rate of decrease compared to Case 1, in Case 2 reached 3.9% at noon, while in Case 3 reached 3% at 02:00 pm, and Case 4 reached 32.6% at 04:00 pm, The peak hours at 02:00 pm decreased by 1.3 in Case 4 compared to Case 1.

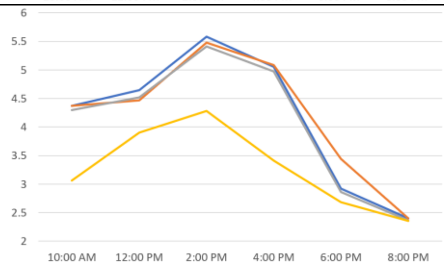
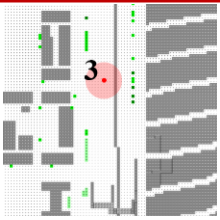
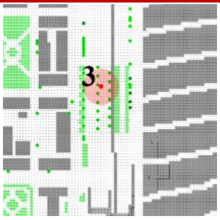


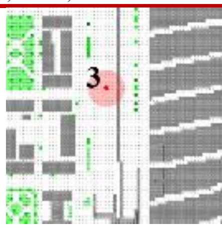
Table 5-32 Point 3 Comparison Between Tair, MRT, and PMV in Area 3.



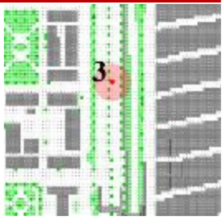
Case 1: Base Case.



Case 2: Parks grass vegetation.



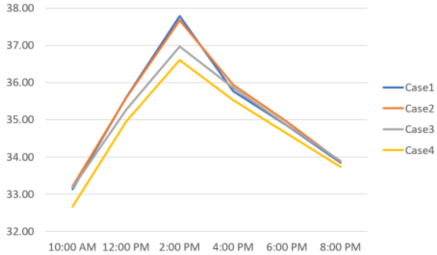
Case 3: Parks tree planting



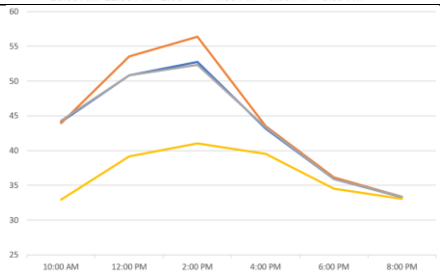
Case 4: Street and parks' vegetation.

POINT 3: Located in the middle of the main street next to the railway line

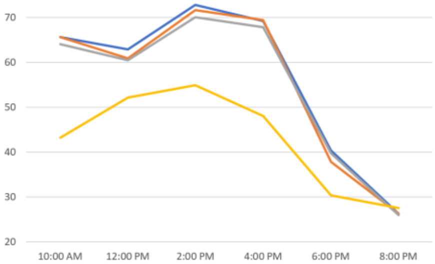
Air Temperature: the maximum rate of decrease compared to Case 1 at 02:00 am, in Case 2 reached 0.3%, while in Case 3, it reached 2.2% and in Case 4 reached 3.1%, The peak hour at 02:00 pm decreased by 1.2°C in Case 4 compared to Case 1.



Surface Temperature: the maximum rate of decrease compared to Case 1, in Case 2 reached 0.3% at 10:00 am, in Case 3 reached 0.7% at noon while Case 4 reached 25.3% at 10:00 am, The peak hours at 02:00 pm decreased by 11.7°C in Case 4 compared to Case 1.



As for MRT: the maximum rate of decrease compared to Case 1, in Case 2 reached 6.3% at 06:00 pm, while in Case 3 reached 3.9% at noon and Case 4 reached 34.2% at 10:00 am, The peak hours at 02:00 pm decreased by 17.9°C in Case 4 compared to Case 1.



As for PMV: the maximum rate of decrease compared to Case 1, in Case 2 reached 4.3% at noon, while in Case 3 reached 5.7% at 02:00 pm, and Case 4 reached 32.1% at 10:00 am, The peak hours at 02:00 pm decreased by 1.3 in Case 4 compared to Case 1.

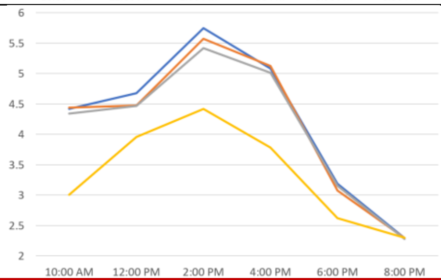
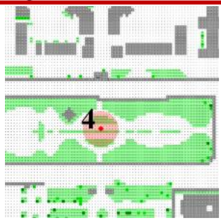
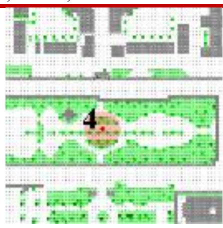
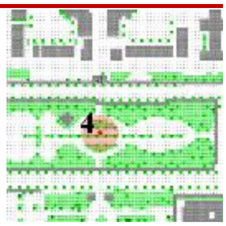


Table 5-33 Point 6 Comparison Between Tair, MRT, and PMV in Area 2.

			
Case 1: Base Case.	Case 2: Parks grass vegetation.	Case 3: Parks tree planting	Case 4: Street and parks' vegetation.

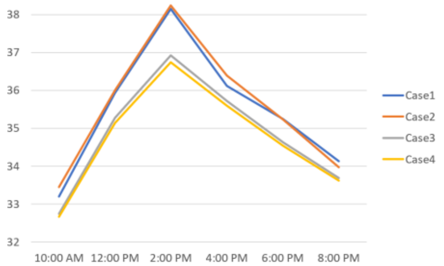
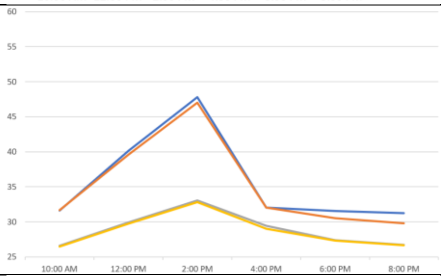
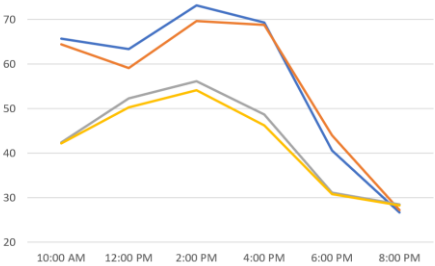
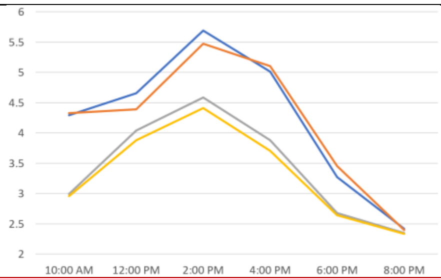
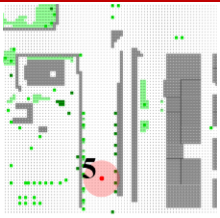
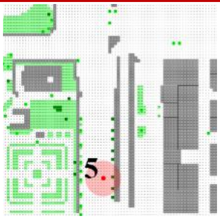
POINT 4: ***Located in the middle of the park***	
Air Temperature: the maximum rate of decrease compared to Case 1, in case 2 reached 0.4% at 08:00 pm, while in Case 3 reached 3.2% at 02:00 pm. In comparison, Case 4 reached 3.7% at 02:00 pm, The peak hour at 02:00 pm decreased by 1.4°C in Case 4 compared to Case 1.	
Surface Temperature: the maximum rate of decrease compared to Case 1, in Case 2 reached 4.7% at 08:00 pm, in Case 3 reached 30.9% at 02:00 pm while Case 4 reached 31.4% at 02:00 pm, The peak hours at 02:00 pm decreased by 15°C in Case 4 compared to Case 1.	
As for MRT: the maximum rate of decrease compared to Case 1, in Case 2 reached 6.8% at noon, while in Case 3 reached 35.5% at 10:00 am and Case 4 reached 35.8% at 10:00 am, The peak hours at 02:00 pm decreased by 19°C in Case 4 compared to Case 1.	
As for PMV: the maximum rate of decrease compared to Case 1, in Case 2 reached 6.9% at noon, while in Case 3 reached 30.4% at 10:00 am, and Case 4 reached 31.1% at 10:00 am, The peak hours at 02:00 pm decreased by 1.3 in Case 4 compared to Case 1.	

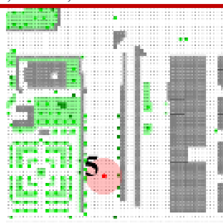
Table 5-34 Point 6 Comparison Between Tair, MRT, and PMV in Area 2.



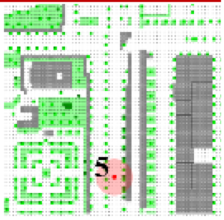
Case 1: Base Case.



Case 2: Parks grass vegetation.



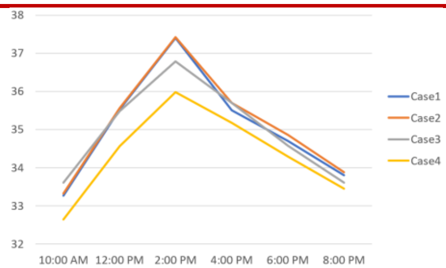
Case 3: Parks tree planting



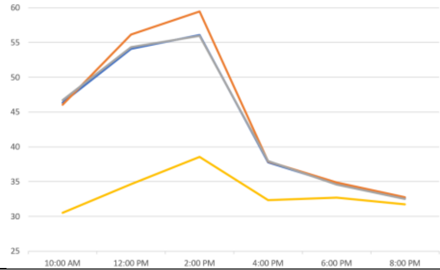
Case 4: Street and parks' vegetation.

POINT 5: Located in the main street

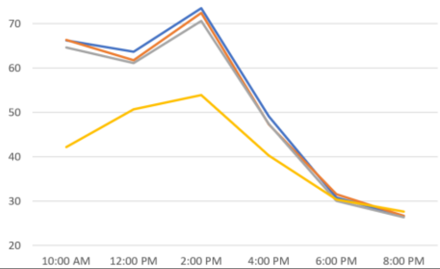
Air Temperature: the maximum rate of decrease compared to Case 1, in Case 3, it reached 1.6% at 02:00 pm. In comparison, Case 4 reached 3.8% at 02:00 pm, The peak hour at 02:00 pm decreased by 1.4°C in Case 4 compared to Case 1.



Surface Temperature: the maximum rate of decrease compared to Case 1, in Case 2 reached 0.6% at 10:00 am, in Case 3 reached 0.4% at 08:00 pm while Case 4 reached 36% at noon, The peak hours at 02:00 pm decreased by 17.5°C in Case 4 compared to Case 1.



As for MRT: the maximum rate of decrease compared to Case 1, in Case 2 reached 3.7% at 04:00 pm, while in Case 3 reached 4.1% at noon and Case 4 reached 36.2% at 10:00 am, The peak hours at 02:00 pm decreased by 19.6°C in Case 4 compared to Case 1.



As for PMV: the maximum rate of decrease compared to Case 1, in Case 2 reached 4.3% at noon, while in Case 3 reached 4.6% at 02:00 pm, and Case 4 reached 33.7% at 10:00 am, The peak hours at 02:00 pm decreased by 1.4 in Case 4 compared to Case 1.

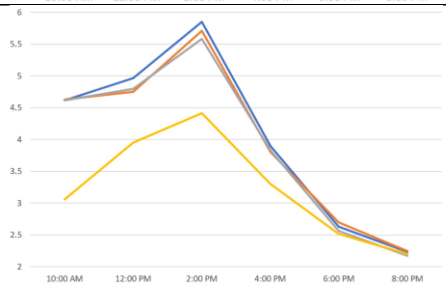
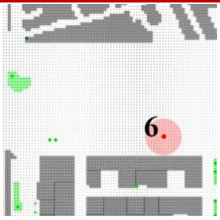
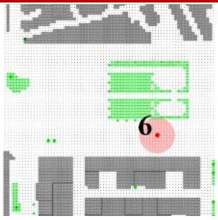


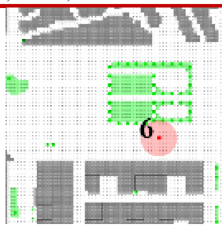
Table 5-35 Point 6 Comparison Between Tair, MRT, and PMV in Area 2.



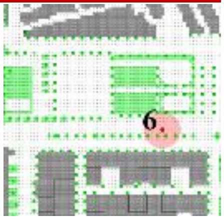
Case 1: Base Case.



Case 2: Parks grass vegetation.



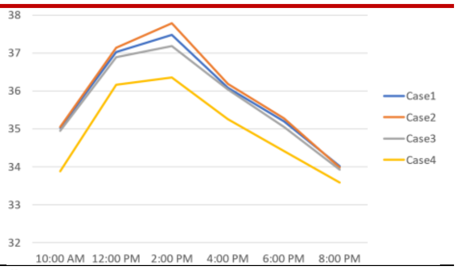
Case 3: Parks tree planting



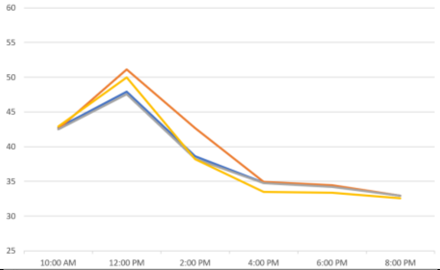
Case 4: Street and parks' vegetation.

POINT 6: Located in the residential area street

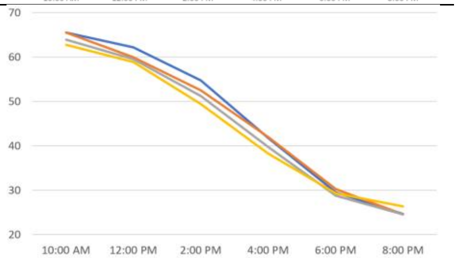
Air Temperature: the maximum rate of decrease compared to Case 1, in case 2 reached 0.1% at 08:00 pm, while in Case 3 reached 0.8% at 02:00 pm. In comparison, Case 4 reached 3.3% at 10:00 am, The peak hour at 02:00 pm decreased by 1.1°C in Case 4 compared to Case 1.



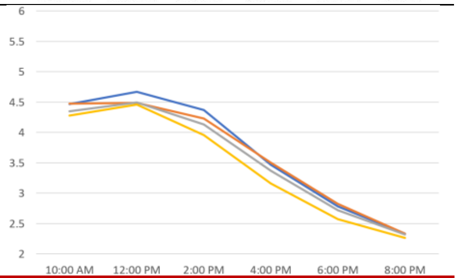
Surface Temperature: the maximum rate of decrease compared to Case 1, in Case 2 reached 0.4% at 10:00 am, in Case 3 reached 0.9% at 02:00 pm while Case 4 reached 3.8% at 04:00 pm, The peak hours at noon decreased by 2°C in Case 4 compared to Case 1.



As for MRT: the maximum rate of decrease compared to Case 1 at 02:00 pm, in Case 2 reached 4.1%, while in Case 3 reached 6.4% and Case 4 reached 9.7%, The peak hours at 10:00 am decreased by 2.8°C at Case 4 compared to Case 1.



As for PMV: the maximum rate of decrease compared to Case 1, in Case 2 reached 4.9% at noon, while in Case 3 reached 5.4% at 02:00 pm, and Case 4 reached 9.5% at 02:00 pm, The peak hours at noon decreased by 0.2 in Case 4 compared to Case 1.



Adding grass only has an unnoticeable change in the thermal performance. However, adding trees in parks only increased the thermal performance in the park's area. Meanwhile, adding trees in streets and parks has the most optimal thermal performance in the entire area.

Table 5-36 The maximum decrease in Tair, MRT, Ts, and PMV at each point in the three Cases.

		Max percentage of Decrease in Case 2				Max percentage of Decrease in Case 3				Max percentage of Decrease in Case 4			
		Tair	**Ts**	**MRT**	**PMV**	**Tair**	**Ts**	**MRT**	**PMV**	**Tair**	**Ts**	**MRT**	**PMV**
Area 1	**Point 1**	3.6 %	26.4 %	38.4 %	32.2 %	4.5 %	27.8 %	40.4 %	34.3 %	4.5 %	27.4 %	41.2 %	35.1 %
	Point 2	4.1 %	31.6 %	33.5 %	38 %	2.8 %	33.6 %	40.3 %	39.6 %	5 %	33.7 %	41.5 %	42 %
	Point 3	1.2 %	29.5 %	33.8 %	29.7 %	0.8 %	0.2 %	4.1 %	4.3 %	2.1 %	30.5 %	36.6 %	33 %
	Point 4	0.3 %	0.4 %	3.5 %	2.7 %	1.6 %	2.4 %	8.3 %	20.8 %	1.6 %	2.3 %	9.6 %	22.2 %
	Point 5	2.3 %	14.7 %	31.5 %	32.2 %	3.2 %	16.3 %	33.4 %	33.8 %	3.2 %	16.1 %	34.5 %	34.7 %
	Point 6	0.8 %	1.4 %	0.4 %	2.8 %	2.6 %	13.8 %	34.4 %	29.2 %	2.7 %	13.7 %	35.4 %	29.8 %
Average		2 %	17 %	24%	23%	**3%**	16%	27%	27%	**3%**	21%	**33%**	**33%**
Area 2	**Point 1**	0 %	8.1 %	1.3 %	0 %	0 %	8.4 %	4.1 %	3.4 %	1 %	5.7 %	6.4 %	5.4 %
	Point 2	0.1 %	0.1 %	0 %	0 %	1.1 %	0.7 %	2.4 %	3.8 %	2.3 %	15.3 %	34.1 %	27.3 %
	Point 3	0 %	0 %	0 %	0 %	0.3 %	0.9 %	4.6 %	4 %	3.4 %	37.8 %	33 %	24.3 %
	Point 4	0.4 %	0 %	0.3 %	0 %	6 %	26.3 %	37 %	29.8 %	6.3 %	26.8 %	38.4 %	31.6 %
	Point 5	0.1 %	0 %	0 %	0.1 %	1.4 %	24.3 %	38.4 %	24.9 %	2.5 %	25 %	39.8 %	26.8 %
	Point 6	0.3 %	0.2 %	0 %	0 %	2.1 %	1.2 %	2.5 %	4.6 %	2 %	6.8 %	7.5 %	4.3 %
	Point 7	0.6 %	0.2 %	0 %	0.1 %	2.7 %	1.3 %	2.5 %	5 %	2.6 %	23 %	21.1 %	4.6 %
	Point 8	0.4 %	0 %	0.3 %	0.6 %	1.9 %	2.8 %	22.7 %	17 %	2.1 %	3.1 %	23.5 %	17.9 %
Average		0.24%	1%	0.24%	0.1%	2%	8%	14%	12%	**3%**	**18%**	**25%**	**18%**
Area 3	**Point 1**	0.1 %	1.4 %	6.4 %	7.4 %	1.9 %	13.3 %	40.7 %	32.3 %	2.2 %	14.5 %	42.7 %	34.1 %
	Point 2	0.1 %	0.6 %	3.2 %	3.9 %	0.4 %	0.3 %	4.1 %	3 %	1.3 %	27.6 %	42.1 %	32.6 %
	Point 3	0.3 %	0.3 %	6.3 %	4.3 %	2.2 %	0.7 %	3.9 %	5.7 %	3.1 %	25.3 %	34.2 %	32.1 %
	Point 4	0.4 %	4.7 %	6.8 %	6.9 %	3.2 %	30.9 %	35.5 %	30.4 %	3.7 %	31.4 %	35.8 %	31.1 %
	Point 5	0 %	0.6 %	3.7 %	4.3 %	1.6 %	0.4 %	4.1 %	4.6 %	3.8 %	36 %	36.2 %	33.7 %
	Point 6	0.1 %	0.4 %	4.1 %	4.9 %	0.8 %	0.9 %	6.4 %	5.4 %	3.3 %	3.8 %	9.7 %	9.5 %
Average		0.17%	1%	5%	5%	2%	8%	16%	14%	**3%**	**23%**	**33%**	**29%**

From Table 5-36 That summarizes the maximum decrease in Ta, MRT and PMV in each case, it was found that:

In Area 1:

The first scenario (case 2): Adding a large park with dense trees and vegetation: the maximum rate of decrease in air temperature was 4.1%, the surface temperature was 31.6%, the MRT was 38.4% and the PMV was 38%, while the average rate of decrease in air temperature was 2%, the surface temperature was 18%, the MRT was 24% and the PMV was 23%.

The second scenario (case 3): Adding dense trees in streets only: the maximum rate of decrease in air temperature was 4.5%, the surface temperature was 44.59%, the MRT was 40.4% and the PMV was 39.6%, while the average rate of decrease in air temperature was 3%, the surface temperature was 23%, the MRT was 27% and the PMV was 27%.

The third scenario (case 4): Adding a large park and dense trees in streets: the maximum rate of decrease in air temperature was 4.5%, the surface temperature was 33.7%, the MRT was 41.5% and the PMV was 42%, while the average rate of decrease in air temperature was 3%, the surface temperature was 21%, the MRT was 33% and the PMV was 33%.

In Area 2:

The first scenario (case 2): Adding parks with dense grass only: the maximum rate of decrease in air temperature was 0.6%, the surface temperature was 8.1%, the MRT was 1.3% and the PMV was 0.6%. While the average rate of decrease in air temperature was 0.24%, the surface temperature was 1%, the MRT was 0.24% and the PMV was 0.1%.

The second scenario (case 3): Adding dense trees in the parks: the maximum rate of decrease in air temperature was 6%, the surface temperature was 26.3%, the MRT was 38.4% and the PMV was 29.8%. while the average rate of decrease in air temperature was 2%, the surface temperature was 8%, the MRT was 14% and the PMV was 12%.

The third scenario (case 4): Adding dense trees in the park and the streets: the maximum rate of decrease in air temperature was 6.3%, the surface temperature was 37.8%, the MRT was 39.4% and the PMV was 31.6%. While the average rate of decrease in air temperature was 3%, the surface temperature was 18%, the MRT was 25% and the PMV was 18%.

In Area 3:

The first scenario (case 2): Adding parks with dense grass only: the maximum rate of decrease in air temperature was 0.4%, the surface temperature was 4.7%, the MRT was 6.8% and the PMV was 7.4%. While the average rate of decrease in air temperature was 0.17%, the surface temperature was 1%, the MRT was 5% and the PMV was 5%.

The second scenario (case 3): Adding dense trees in the parks: the maximum rate of decrease in air temperature was 3.2%, the surface temperature was 30.9%, the MRT was 40.7% and the PMV was 32.3%. While the average rate of decrease in air temperature was 2%, the surface temperature was 8%, the MRT was 16% and the PMV was 14%.

The third scenario (case 4): Adding dense trees in the park and the streets: the maximum rate of decrease in air temperature was 3.8%, the surface temperature was 36%, the MRT was 42.7% and the PMV was 34.1%. While the average rate of decrease in air temperature was 3%, the surface temperature was 23%, the MRT was 33% and the PMV was 29%.

The analysis of the three cases in three areas that shared the same climate characteristics demonstrated that the integration of trees in both parks and streets improved thermal performance in all areas. However, the percentage of tree planting is different in each case and each area. Table 5-37 and Table 5-38 is a comparison between the three areas to determine the area with the most optimal thermal performance.

Table 5-37 The Green Coverage and the Average Tair, MRT and PMV for the Three Areas.

		Area 1	Area 2	Area 3
Green coverage	Base case	1%	10%	6%
	Parks tree planting	6%	25%	15%
	Streets and parks tree planting	20%	35%	25%
Tair	Base case	35-36.3°C	35.3-36.7°C	34.2-36.6°C
	Parks tree planting	34.3-35.9°C	34.8-36.4°C	34.2-36.2°C
	Streets and parks tree planting	34.2-35.1°C	34.5-35.6°C	33.8-35.5°C
T surface	Base case	35.6-47°C	37.6-46.3°C	33-46.3°C
	Parks tree planting	26.3-47°C	29-44.3°C	25-45.5°C
	Streets and parks tree planting	26.3-40.3°C	27-40.3°C	25-35°C
MRT	Base case	54-62°C	59-64°C	59-64°C
	Parks tree planting	47-60°C	47-63°C	47-62°C
	Streets and parks tree planting	39-49°C	42-59°C	40-57°C
PMV	Base case	4.1-4.8	4.5-5.2	4.2-5
	Parks tree planting	3.3-4.8	3.6-4.9	3.3-4.7
	Streets and parks tree planting	3.1-3.9	3.3-4.8	3.2-4.2

Table 5-38 Average Decrease in Tair, MRT and PMV for the Three Areas compared to the base cases.

		Area 1	**Area 2**	**Area 3**
Tair	Parks tree planting	0.2-0.4°C	0.5-0.3°C	0.4°C
	Streets and parks tree planting	0.8-1.2°C	0.8-1.1°C	0.4-1.1°C
T surface	Parks tree planting	9.3°C	2-8.6°C	0.8-8°C
	Streets and parks tree planting	6.7-9.3°C	6-10.6°C	8-11.3°C
MRT	Parks tree planting	1-7°C	1-12°C	2-12°C
	Streets and parks tree planting	13-15°C	5-17°C	7-19°C
PMV	Parks tree planting	0.8	0.3-0.9	0.3-0.9
	Streets and parks tree planting	0.9-1	0.4-1.2	0.8-1

By analyzing Table 5-37 and Table 5-38 it was found that:

- Adding trees to both parks and streets improves thermal performance more effectively than adding trees only to parks across all areas.
- The improvement in thermal performance is most significant in Area 2 due to the higher percentage of green coverage.

The use of grass only in areas 2 and 3, the maximum rate of decrease in air temperature was 0.6%, the surface temperature was 8.1%, the MRT was 6.8% and the PMV was 7.4%. While the average rate of decrease in air temperature was 0.21%, the surface temperature was 1.19%, the MRT was 2.3% and the PMV was 2.3%.

The use of parks in areas 1, 2, and 3 resulted in a maximum rate of decrease in air temperature of 6%, a surface temperature of 31.6%, an MRT of 40.7%, and a PMV of 38%, while the average rate of decrease was 1.9%, a surface temperature of 10.9%, an MRT of 17.5%, and a PMV of 15.6%.

The use of streets-only tree planting in area 1 resulted in a maximum rate of decrease in air temperature of 4.5%, a surface temperature of 44.59%, an MRT of 40.4%, and a PMV of 39.6%, while the average rate of decrease was 3%, a surface temperature of 23%, an MRT of 27%, and a PMV of 27%.

The use of a connective green network (the parks and vegetated streets) in areas 1, 2, and 3 resulted in a maximum rate of decrease in air temperature of 6.3%, a surface temperature of 37.8%, an MRT of 42.7%, and a PMV of 42%, while the average rate of decrease was 3%, a surface temperature of 20.3%, an MRT of 30%, and a PMV of 26%.

5.8. Conclusion

This chapter analyzes urban green infrastructure scenarios in three areas in Al-Mahalla Al-Kubra city using ENVI-met a computer climatic simulation program, according to three scenarios in each area, the scenarios in the first area were, the first scenario was designing a large park in the area, the second scenario was adding dense trees in the streets only, while the third one was designing the park and adding dense trees in the street. Scenarios in the other two areas were the first scenario was adding grass only in the parks, the second scenario was adding dense trees in the parks, and the third one was adding dense trees in the parks and the street. It was found that:

- Adding grass only in the area the average rate of decrease in air temperature was nearly 0.5%, on the other side adding tree planting in the parks without urban green infrastructure connectivity the maximum rate of decrease in air temperature was 2%. Meanwhile, with urban green infrastructure connectivity, the air temperature decreased by 3%,

- Adding grass only in the area the average rate of decrease in surface temperature was nearly 1%, on the other side adding tree planting in the parks without urban green infrastructure connectivity a maximum rate of decrease of 11%. Meanwhile, with urban green infrastructure connectivity, decreased by 20%,
- Adding grass only in the area the average rate of decrease in MRT was nearly 2%, on the other side adding tree planting in the parks without urban green infrastructure connectivity with a maximum rate of decrease of 18%. Meanwhile, with urban green infrastructure connectivity, decreased by 30%,
- Adding grass only in the area the average rate of decrease in PMV was nearly 2%, on the other side adding tree planting in the parks without urban green infrastructure connectivity a maximum rate of decrease of 16%. Meanwhile, with urban green infrastructure connectivity, decreased by 26%,
- Adding grass only has a neglected effect on the air temperature, MRT and PMV. Meanwhile, it decreases the surface temperature.

According to the previous study, implementing green infrastructure principles and establishing a green network reduced urban heat islands in existing cities.

CHAPTER 6

CONCLUSION

Addressing the urban heat island (UHI) phenomenon, a critical consequence of rapid urbanization and climate change is urgent. As urban areas grow in population and density, heat accumulation and its associated impact ranging from reduced thermal comfort to increased health risks and environmental degradation present significant challenges. The UHI effect is not only a cause of local climate change, but it also causes deeper ecological and social issues that require quick and innovative solutions.

Green infrastructure (GI) comes out as a promising, long-term, and multifaceted strategy for mitigating the UHI effect. By incorporating natural and semi-natural systems into urban planning, GI provides shade, improves evapotranspiration cooling, and reduces heat accumulation. Furthermore, GI provides ecological, social, and economic benefits such as improved air quality, increased biodiversity, and greater urban resilience.

The study discussed the process of UHI, analyzed the role of GI in mitigating its effects, and evaluated its practical applications using analytical tools and case studies, with a focus on hot and dry climate zones including El-Mahalla El-Kubra as an applied study using ENVI-met simulation program. The research aims to study the effectiveness of green infrastructure in reducing urban heat island (UHI) phenomena and creating healthier, more livable urban environments in existing cities, through theoretical, analytical, and applied studies, it was found that:

The theoretical approach:

- The term "urban heat island" typically refers to the increased air temperature near the ground, known as the canopy layer.
- Atmospheric UHI is small or non-existent during the day and most intense at night, while surface UHI presents all day and is most intense during summer.
- Atmospheric UHI has two types: boundary layer UHI (BLUHI) and canopy layer UHI (CLUHI)
- The reduction of using heat and cooling applicants helps in reduce air temperature and UHI.
- The use of impervious surfaces reduces air temperature due to evapotranspiration.
- Materials with high albedo and high thermal emissivity stay cooler.

- The ratio of built-up areas to green spaces relates to UHI; as green spaces increase, the UHI decreases.
- The cities' urban geometry, size and form affected wind flow in the city helps in reducing air temperature, which affected UHI.
- The pollutants, weather conditions and geographic location all affected UHI.
- UHI has a significant negative impact economically, environmentally, socially, and biologically,
- Urban Heat Islands (UHI) primarily have negative impacts on the environment, directly affecting social, biological, and economic aspects.
- UHI mitigation strategies can be categorized based on scale: at the urban scale, methods include green roofs, green walls, and cool roofs, while at the building scale, they involve green coverage and cool pavements.
- Green roofs and green coverage offer more functions compared to cool roofs and cool pavements.
- UHI mitigation strategies primarily focus on cooling surfaces through shading, evaporation, or the use of reflective high-albedo materials. Green infrastructure incorporates these properties to help reduce UHI and improve the built environment into a harmonious blend of ecological functionality and human livability.
- Green infrastructure is defined as "an interconnected network of green spaces that preserves natural ecosystem functions and values while offering benefits to human populations."
- Green infrastructure practices not only help in reducing air temperature but also help in stormwater management.
- The principles of green infrastructure (GI) offer a strategic approach and framework for conservation, promoting the sustainable use of land while benefiting people, wildlife, and the economy.
- The integration of green and gray infrastructure in urban planning combines green spaces with transportation networks and utility systems, includes elements such as green corridors, street tree canopies, green walls, and greenery in parking areas.

- Connectivity is establishing and restoring green space networks focusing on landscape networks to facilitate or inhibit movement and flow.
- Multifunctionally enhancing the ecological, socio-cultural, and economic benefits of urban green spaces.
- Urban Green Infrastructure (UGI) planning fosters social inclusion by promoting collaborative processes, balancing interests, and ensuring equitable access to green space services.
- UGI planning integrates multiple spatial levels to enhance air and water quality, establish ecological corridors, and promote equitable green space access.
- A green infrastructure network includes all types of urban green and blue spaces, regardless of ownership or origin.
- UGI planning unites disciplines, science, policy, and practice through collaboration with local governments and stakeholders.
- Green infrastructure enhances environment, biological economic and social functions.
- A green roof is a vegetated rooftop that provides shade, promotes evapotranspiration and lowers temperatures. Suitable for various buildings, it helps reduce ambient air temperatures.
- Green walls, also known as living walls or vertical gardens, support plant growth on exterior walls.
- Tree planting and green roofs reduce air temperature by shading and evapotranspiration.
- Bioretention and infiltration practices, permeable pavements and water harvesting reduce air temperature by evapotranspiration.
- Green infrastructure practices seek to integrate ecological and hydrological processes to support sustainable urban development through an ecology-based approach.

The analytical approach:

- The use of satellite-based sensors and GIS programs helped define thermal maps for existing areas and cities in the past.
- Green infrastructure network connectivity lowers the land surface temperature in urban areas.

- The integration of blue-green infrastructure helps in lowering the land surface temperature and air temperature in urban areas.
- As the percentage of green areas increases, the thermal comfort increases.
- The use of dense tree shadow decreases LST than the palm trees.
- The large areas of parks without high GI network reflected on LST in making parks cool island effect,
- In The areas with denser vegetation, the LST has decreased compared to surrounding areas with an average temperature of about (2˚C) during the day and about (1˚C) at night.

The applied approach:

- Using simulation programs helps evaluate the effectiveness of different scenarios on the air temperature, surface temperature, mean radiant temperature and thermal comfort in specific data before implementation.
- Adopting green infrastructure principles helps in reducing UHI, especially connectivity and green-grey integration, as adding a green network can reduce the air temperature by 3%, the surface temperature by 20.3%, the mean radiant temperature by 30%, and the predicted mean vote by 25.6%, which affects urban heat island reduction in existing cities.
- Adding grass vegetation has no effect in lowering air temperature or the mean radiant temperature; it only lowers the surface temperature.
- Adding trees that provide sufficient shading helps in lowering air temperature, surface temperature and mean radiant temperature.
- As the percentage of green coverage increases, the thermal comfort increases.

Overall, the study finds that urban green infrastructure principles in city planning are essential for urban heat island reduction in existing cities and can save the city’s future from the risk of such a phenomenon.

Recommendations

It is recommended that architects, urban designers, and planners:

- Implement green infrastructure including shrubs and tree canopies into grey infrastructure such as transport, bridges, pavements, and buildings to optimize cooling effects, and avoid relying on grass vegetation only, as it provides limited thermal benefits, instead tree planting provides better thermal performance.
- Reduce vehicle use by encouraging walkability and integrating green spaces within high-density developments.
- Utilize high-albedo and permeable materials by adopting reflective and high-emissivity materials in urban surfaces, such as cool pavements and reflective rooftops, to minimize heat absorption.
- Adopt green infrastructure principles to lower urban temperatures, improve air quality, and enhance thermal comfort. These strategies create sustainable and climate-resilient urban environments.
- Increase the quantity and quality of urban parks and open green areas, focusing on densely built neighborhoods. These spaces should be designed with multifunctionality in mind, offering recreation, biodiversity support, and microclimatic regulation.
- Incorporate water bodies, rain gardens, and bioretention systems to improve cooling through evaporation and moisture retention.
- Use climate simulation software like ENVI-met to assess the impact of green infrastructure designs before implementation.
- Use satellite imaging and GIS for thermal mapping to monitor UHI intensity and assess the effectiveness of mitigation strategies over time.
- Select plant species based on their suitability for the urban microclimate. Trees should provide dense shade in summer and allow sunlight to penetrate during winter, balancing thermal comfort throughout the year.
- Select trees that provide sufficient shading to provide thermal comfort.

- Ensuring environmentally responsive design in new urban developments is essential to prevent the emergence of Urban Heat Island (UHI) phenomena in the future.
- Adjust building heights, street orientation, and spacing to promote natural ventilation.

It is recommended that governments and decision-makers:

- Consider formulating supportive policies that encourage the use of green infrastructure in urban development and ensure the provision of adequate funding for sustainable design initiatives.
- Implement Urban Heat Island (UHI) mitigation regulations by introducing guidelines that ensure a minimum percentage of green coverage in urban developments, helping to reduce heat accumulation and enhance urban resilience.
- Promote education among urban planners and decision-makers by organizing training programs and workshops for policymakers, architects, and developers to highlight the benefits and implementation strategies of green infrastructure.
- Enhance community engagement by involving stakeholders and local communities in green infrastructure projects to promote stewardship, maintenance, sustainability and long-term success.
- Encourage residents to adopt GI practices such as urban gardening, green roofs, and tree planting in their neighborhoods.
- Enhance Green Infrastructure by prioritizing the development of parks and green roofs in underserved neighborhoods.
- Raise awareness among urban planners, policymakers, and residents about the benefits of green infrastructure and the importance of addressing urban heat island issues through targeted media campaigns and educational initiatives.
- Establish preservation policies and maintenance plans for green infrastructure elements to ensure their longevity, ecological function, and continued contribution to urban resilience.

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الفصل الخامس:

استخدام برنامج المحاكاة ENVI-met لمحاكاة عدة سيناريوهات للبنية التحتية الخضراء في مدينة المحلة الكبرى، من خلال تبني مبادئ البنية التحتية الخضراء وتحليل فعاليتها في تقليل تأثير ظاهرة الجزيرة الحرارية، من خلال دراسة درجة حرارة الهواء، ودرجة حرارة السطح، ومتوسط درجة الحرارة الاشعاعية، ومستويات الراحة الحرارية في المناطق العمرانية.

- **الفصل السادس** :

يتضمن استنتاجات والتوصيات الدراسة.

هدف البحث

تهدف الدراسة الي تطوير حلول تعتمد على مبادئ البنية التحتية الخضراء كحل فعال ومستدام للتقليل من ظاهرة الجزيرة الحرارية في المدن القائمة.

الأهداف الفرعية:

- **تحسين الراحة الحرارية للعمران** :من خلال تطوير استراتيجيات لتحسين مستويات الراحة الحرارية في الشوارع والمناطق العمرانية، مما يوفر ظروف معيشية أفضل للسكان.
- **التخفيف من تأثير الجزيرة الحرارية وتغيير المناخ** :من خلال دمج آليات التبريد الطبيعية في التصميم العمراني.
- **تعزيز التصميم العمراني المستدام** :من خلال اعتماد مبادئ البنية التحتية الخضراء لتحويل المدن الحالية إلى بيئة أكثر صحة ومرونة واستدامة.

هيكل الدراسة

تتكون الدراسة من ستة فصول:

- **الفصل الأول**:
مقدمة عامة تتضمن نظرة عامة على الدراسة، ومشكلة البحث، وأهداف البحث، والفرضيات، والأهداف، والمنهجية.

- **الفصل الثاني** :
تعريف ظاهرة الجزيرة الحرارية، وأنواعها، والعوامل المؤثرة عليها، وأسباب اختلاف شدتها، اثرها الاقتصادي والبيئي والاجتماعي والبيولوجي، بالإضافة إلى استراتيجيات التخفيف منها.

- **الفصل الثالث** :
تعريف مفهوم البنية التحتية الخضراء، وعناصرها، والمبادئ الأساسية لتصميمها، ووظائفها البيئية، والبيولوجية، والاقتصادية، والاجتماعية، مع ملخص لتطبيقات البنية التحتية الخضراء.

- **الفصل الرابع** :
تحليل تأثير استخدام عناصر ومبادئ البنية التحتية الخضراء في بعض المناطق العمرانية القائمة محليًا ودوليًا، والتي اعتمدت على البنية التحتية الخضراء في تصميمها العمراني، لتقييم فعاليتها في تحسين الأداء الحراري ضمن نطاق مناخي واحد.

الملخص

أدى التحضر السريع والاكتظاظ السكاني إلى جانب نقص المساحات الخضراء، إلى زيادة درجة حرارة الهواء وانخفاض معدل الراحة الحرارية في المناطق الحضرية الكثيفة وانخفاض جودة الهواء وزيادة ظاهرة الجزر الحرارية الحضرية، خاصا في المدن الحضرية القائمة .ونتيجة لذلك، يهدف البحث إلى تقليل تأثير ظاهرة الجزيرة الحرارية وتحسين الأداء الحرارية للمدن المصرية القائمة من خلال اعتماد مبادئ البنية التحتية الخضراء وإثبات فعاليتها على ظاهرة الجزيرة الحرارية .يركز هذا البحث على ظاهرة الجزيرة الحرارية باعتبارها واحدة من القضايا البيئية التي تواجه التوسع الحضري ويتضمن مراجعة للبنية التحتية الخضراء كواحدة من استراتيجيات التخفيف .بالإضافة إلى تحليل بعض المناطق الحضرية القائمة المختلفة التي تستخدم البنية التحتية الخضراء في تصميمها الحضري لتقييم مدى فعاليتها على الأداء الحرارية الحضري، يتضمن البحث أيضًا دراسة تطبيقية على مدينة المحلة الكبرى بمحافظة الغربية بمصر، حيث تتم دراسة وتحليل سيناريوهات مختلفة للبنية التحتية الخضراء باستخدام برنامج المحاكاة البيئية للتعرف على تأثيرها على الأداء الحراري من خلال تحليل درجة حرارة الهواء ومتوسط درجة الحرارة المشعة ودرجة حرارة السطح ومتوسط التصويت المتوقع، والتي تؤثر على ظاهرة الجزيرة الحرارية. وتظهر النتائج أن اعتماد مبادئ البنية التحتية الخضراء له تأثير كبير على خفض درجة حرارة الهواء ومتوسط درجة الحرارية الإشعاعية وتحسين الراحة الحرارية، مما يؤكد على فاعلية البنية التحتية من الحد من ظاهرة الجزيرة الحرارية.

جامعة طنطا

كلية الهندسة

قسم الهندسة المعمارية

البنية التحتية الخضراء كمدخل لتقليل تأثير الجزيرة الحرارية في المدن القائمة

رسالة علمية مقدمة كجزء من متطلبات الحصول على درجة ماجستير العلوم في الهندسة المعمارية بكلية الهندسة – جامعه طنطا

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2025

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