Towards the Oasis

Assessing Urban Green Infrastructure for Heat Resilience and Nature-Based Cooling in Arid Climates: A Case Study of Riyadh

Master Thesis - Engineering and Policy Analysis

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Project Duration:	2024, March - 2024, December
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Cover: Riyadh, Saudi Arabia

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Acknowledgements

I would like to thank Egis, particularly the Green Riyadh Project Management Office, and the Royal Commission for Riyadh City for their collaboration. I also extend my gratitude to the team at Bödeker Landscape Architects for their valuable insights and contributions to my research. Special thanks go to Prof.dr. Jill Slinger for introducing me to the concept of Nature-based Solutions, which inspired me to explore this topic in greater depth. I would also like to thank Dr. Haiko van der Voort for his encouragement and assistance throughout this process. I am genuinely appreciative of Floris, Lian, Nachiket, Rhys, Yashi, and Timothy for the late nights spent studying together at the library. I am also thankful to my father for introducing me to the Kingdom of Saudi Arabia, which has shaped my interest in this research. Finally, I dedicate this work to my late mother, whose enduring inspiration and guidance continue to influence everything I pursue.

Abstract

This study explores the potential of Nature-based Solutions (NbS), specifically green roofs and walls, to mitigate extreme heat in arid urban environments like Riyadh. Using fieldwork, interviews, and remote sensing, a microclimate model is developed to assess the feasibility and effectiveness of these interventions. Findings highlight that combined green roofs and walls provide the greatest cooling benefits, reducing temperatures by up to 1.31°C for the tested scenarios, but come with significant challenges, including high costs, structural limitations, water scarcity, and maintenance needs. Reflective coatings emerged as a cost-effective alternative, offering consistent but modest cooling. The study emphasizes the need for targeted, localized cooling efforts and raises concerns about the feasibility of widespread green infrastructure implementation in arid regions.

Contents

Lexicon

Modelling Terms	
Baseline Simulation	A reference simulation conducted without any green infrastructure to establish the current microclimate conditions in an area, including UHI effects.
ENVI-met	A simulation tool used for modelling surface-plant-air interactions in urban environments. It helps assess the effects of green infrastructure on microclimates, including temperature and air quality changes.
Green Roofs (GR)	Roofs covered with vegetation, designed to reduce building temperatures, improve air quality, and provide insulation. GRs are analyzed for their potential to mitigate UHI effects.
Green Walls (GW)	Vegetation-covered vertical structures used to cool building surfaces and improve air quality by absorbing heat and pollutants.
Height-Specific Analysis	Temperature simulations conducted at specific heights (e.g., 140 cm for children and 180 cm for adults) to assess the localized cooling effects of green infrastructure on microclimates at varying human-relevant levels.
Housing Block	A building configuration consisting of four houses horizontally and two vertically, forming a typical residential unit in the study's model. This was used to replicate residential areas in Al Malaz for the ENVI-met simulations.
North-, South-, East-, and West-Facing Walls	Building facades oriented in specific directions, analyzed for temperature variations due to sunlight exposure.
Perceived Temperature	A measure of how humans experience temperature, influenced not only by air temperature but also by factors such as humidity, wind, and surface heat radiation.
Reflectivity / White Walls	The property of materials to reflect solar energy. White walls are used in simulations to compare their cooling effects with those of green infrastructure.
Story Height	The vertical height of one building story. In this study, typical story heights of 6–9 m for two-story buildings and 9–12 m for three-story buildings were used in the simulation.
Temperature Dispersion Patterns	Variations in temperature across a building's surfaces and immediate surroundings, observed in different scenarios (e.g., green roofs, green walls, white walls).
Time-of-Day Analysis	A method used to compare cooling effects at different times (e.g., 8 am, 3 pm, and 10 pm) to understand how interventions perform under changing solar radiation conditions.
Urban Green Infrastructure (UGI)	Infrastructure such as green roofs, walls, parks, and urban forests integrated into city planning to improve sustainability, manage stormwater, and reduce UHI effects.
Urban Heat Island (UHI) Effect	A phenomenon where urban areas become significantly hotter than their rural surroundings due to the dense concentration of heat-absorbing materials like concrete and asphalt.
Remote Sensing Terms	
Band 4 (NIR)	The Near-Infrared band from Landsat 8 used to calculate NDVI, which is crucial for assessing vegetation health.
Band 5 (RED)	The Red band from Landsat 8 used in conjunction with the NIR band for NDVI calculations.
Band 10 (TIRS)	The Thermal Infrared Sensor band from Landsat 8, used for retrieving Land Surface Temperature (LST) via the Mono-Window Algorithm.

Land Surface Temperature (LST)	The temperature of the Earth's surface, as measured by satellite thermal sensors. LST is crucial for understanding the heat dynamics in urban areas, particularly in relation to UHI effects.
Landsat 8	A satellite that provides imagery for environmental monitoring, including bands for vegetation analysis (NIR and RED) and thermal infrared data for LST analysis.
Mono-Window Algorithm	A method used to calculate LST from satellite thermal infrared data. It adjusts for atmospheric conditions and land surface emissivity to provide accurate temperature readings from remote sensing data.
Satellite Imagery	Images captured by satellites like Landsat 8, used in this study to assess vegetation, land-use, and surface temperature.
Normalized Difference Vegetation Index (NDVI)	A vegetation index derived from satellite imagery that measures vegetation health by comparing reflectance in the Near-Infrared (NIR) and Red (RED) bands. NDVI values range from -1 to 1, with higher values indicating more prominent vegetation.
Pre-set Vegetation (ENVI-met)	Vegetation options pre-configured within ENVI-met, representing typical urban species suitable for the simulated environment.
Interviews and Data Collection	
ArcGIS Pro	A geographic information system (GIS) software used for processing satellite images, calculating NDVI, merging spatial data, and conducting the spatial analysis of Riyadh's urban environment.
Cloud Interference	A factor in remote sensing that can obstruct accurate data collection. Images in this study were manually checked to ensure minimal cloud coverage before conducting further analysis.
Expert-Specific Questions	Questions tailored to the interviewee's area of expertise, focusing on specific technical aspects, such as green roofs, irrigation systems, and urban planning.
Field Measurements	Measurements taken from the built environment, such as building height, street width, and housing block dimensions, to create an accurate simulation model of the Al Malaz district.
Google Street View and Fieldwork	Tools and techniques used to observe and analyze the most frequent building types and layouts in Al Malaz, supporting the construction of the digital twin model.
Iterative Question Development	A process of refining interview questions to ensure they are aligned with the research goals while complying with ethical guidelines (such as anonymity).
Urban Green Infrastructure Ratios (GR/UGI ratios)	Ratios of green roofs and other green infrastructure implemented in simulation models (e.g., 25%, 50%, 75%, 100%) to analyze their effects on the UHI.
Semi-Structured Interviews	A qualitative research method used in this study to gather insights from experts. It combines pre-determined questions with the flexibility for interviewees to provide detailed, open-ended responses.
Spatial Analysis	The process of analyzing the geometry of urban environments using satellite imagery and GIS software, such as ArcGIS Pro, to assess the layout of buildings, streets, and land-use patterns.

1

Introduction

1.1. Context

Today, more than half of the world's population resides in urban areas. This number is projected to grow to 68% by 2050, with the largest growth in urban population shares in non-western regions (UN DESA, 2018). High population density leads to intensified land use, introducing an increased amount of impervious and heat-retaining surfaces, which in turn exacerbate urban challenges such as greenhouse gas emissions, air pollution and overheating (Frantzeskaki et al., 2019, Sarabi et al., 2019). These factors make urban areas hotter than non-urbanised, or rural areas while amplifying climate change (Gunawardena et al., 2017). Nature-based solutions (NbS) could help mitigate these effects, and offer a sustainable and resilient alternative to the conventional "grey infrastructure" (Frantzeskaki et al., 2019), i.e., the concrete structures that most cities are currently composed of.

NbS describe various actions addressing societal challenges which are either inspired, supported or copied from nature or natural phenomena (Sarabi et al., 2019). Nature-based solutions are sustainable resolutions rooted in ecological processes to address societal challenges and hopefully improve environmental resilience. Their aim is to promote long-term viability through strategies which are both resource-efficient and low-impact (Wickenberg et al., 2021). A key feature of NbS are their adaptability to local context through various levels of scaling (Frantzeskaki et al., 2019). NbS are believed to be co-beneficial, by promoting environmental, social and economic efforts. Examples of environmental benefits include enhancing biodiversity, reducing greenhouse gas emissions (Raymond et al, 2017), and managing urban flooding. Social benefits include improving public health (Bosch & Sang, 2017) and strengthening the community (Mahmoud & Morello, 2021). Examples of economic benefits include energy cost-reduction, as well as pre-emptive calamity measures.

As urbanization accelerates, cities face escalating challenges from rising temperatures, exacerbated by the urban heat island (UHI) effect. This phenomenon is driven by the replacement of natural landscapes with impervious surfaces, and increases urban temperatures, heightens energy demand, and threatens public health. As such, cities are becoming increasingly vulnerable to extreme heat events. Urban green infrastructure (UGI), such as green roofs and walls, but also parks, floodplains and rain gardens, are a subset of NbS that offer an innovative and promising solution to combat UHI effects by delivering localized cooling, thus reducing energy consumption, and enhancing thermal comfort. UGI is a broad concept, referring to various methods which integrate natural and semi-natural processes within urban areas. Such methods included shading, evapotranspiration, and the albedo effect. By leveraging natural processes, UGI can reduce ambient temperatures, and regulate microclimates. Additionally, it can help improve air quality and increase urban resilience.

Arid regions, with high levels of solar radiation and scarce water resources, are particularly susceptible to severe heat stress. Cities like Riyadh, Saudi Arabia, face distinct challenges in adopting green infrastructure, requiring innovative and region-specific strategies to address these issues effectively. While the benefits of green roofs and walls in mitigating UHI are well-documented in temperate and tropical climates, research on their applicability in arid regions is limited. Existing studies, often focused on continental or tropical climates, cannot grasp the challenges faced when attempting to implement similar methods in water and vegetation-scarce, extremely hot climates. Additionally, they fall short of understanding the logistical barriers unique to these areas, where NbS must balance cooling benefits with efficient water use.

1.2. Case study

This research explores the potential of NbS to enhance sustainability in arid climates, by focusing on Green Riyadh as a case study. Given that Saudi Arabia is one of the most urbanized countries in the world, with 80% of its population residing in cities, integrating green infrastructure into urban planning is vital for improving quality of life and reducing environmental impact (Almatar, 2023). The Green Riyadh project not only exemplifies how UGI can contribute to reducing the Urban Heat Island (UHI) effect, but also presents a framework for improving air quality and enhancing urban resilience through sustainable design. However, the implementation of green infrastructure in an arid environment presents specific challenges, such as the need for drought-resistant plants and innovative irrigation solutions. To achieve these goals, the Green Riyadh initiative emphasizes the use of drought-tolerant plant species suitable for arid climates, with guidelines specifying soil thickness and root depth requirements to ensure sustainability (Manual of Ariyadh Plants). These choices align with the broader objectives of Vision 2030 to increase urban greenery while adapting to the unique environmental challenges posed by the desert landscape.

Saudi Arabia currently seeks to shift from an oil-centred economy to one centred around tourism and research, exemplified by the Saudi Vision 2030 initiative (Projects, n.d.). This ambitious transition was launched in 2019 and involves substantial investments in massive infrastructures and is demonstrated by the emergence of various megaprojects, such as The LINE. Over the last decade, the kingdom has made efforts to shift its economy, but also its foreign and home policy (Mirzoev et. al., 2020). The idea is to move away from prior practices and model their new economy in part to the system developed by Dubai (Mirzoev et. al., 2020; Explained by Dom, 2023). In doing so, Saudi Arabia is reinforcing its position as a key player in world politics. While Saudi Arabia aligns political and financial interests for these projects, the collaborative efforts required from diverse stakeholders should be acknowledged. These projects depend on innovative technologies which cannot be achieved without international contributions: many of these projects require input from international engineering firms (Loo et. al., 2013) as well as foreign investments (El-Awady et. al., 2020). Additionally, these projects have to comply with national environmental sustainability laws (National Center for Environmental Compliance, n.d.), making policymaking difficult surrounding such projects.

Historically, Riyadh, whose name means “gardens,” was a conglomerate of oases, sprawling from the water provided by Wadis Hanifa and Al-Baṭḥā before rapid urbanization transformed it into a sprawling metropolis. Riyadh has expanded beyond its origins as a fortified town, introducing a new problem: a scarcity of green spaces in the city today (Wikipedia, n.d.). Currently, Riyadh offers just 1.18 m² of public open space per capita, well below the WHO recommendation of 9 m², highlighting a critical need for urban greening initiatives (Addas & Maghrabi, 2020). Urban green infrastructure (UGI), such as green roofs and walls, offers a viable solution for adding greenery to densely built areas without expanding further into the desert. Green infrastructure can create pockets of vegetation that provide cooler micro-environments, potentially transforming building rooftops into public or semi-public green spaces.

The Green Riyadh project aims to address these challenges by transforming Riyadh into a “green oasis,” through the integration of Nature-Based Solutions (NbS) that support urban resilience and climate adaptation. This initiative has a goal to plant 7.5 million trees, in order to reduce carbon emissions by 3-6%, and lower city temperatures by 1.5-2°C (Projects, n.d.). However, the city faces unique challenges due to its arid climate and rapid urbanization, which have exacerbated issues like flash flooding. Rapid expansion and impervious surfaces have significantly limited water absorption, thereby increasing surface runoff and the frequency of urban flooding (Nahiduzzaman et al., 2015). These concerns underscore the need for sustainable stormwater management strategies that can be integrated with UGI.

Figure 1.1: View from the Kingdom tower

1.3. Research

Three gaps have been established that this research attempts to address:

1. The lack of context-specific research on green roofs and walls in arid regions (Koc et al., 2018; Yang & Wang, 2017)
2. The barriers to adoption of UGI in arid regions (Jamali et al., 2021)
3. Assessing the feasibility of UGI within arid climates (Cheung et al., 2021)

This study incorporates remote sensing and micro-climate modelling to assess the viability and impact of UGI, using Riyadh as a case study. Using tools like ENVI-met and Landsat 8 satellite imagery, the research evaluates Land Surface Temperature (LST) variations and examines how green roofs and walls can be optimized to improve perceived air temperatures. Furthermore, this research offers insights into how Riyadh can balance environmental sustainability with thermal comfort. Ultimately, this research seeks to bridge the gap in understanding how NbS can be applied effectively in arid urban environments.

By focusing on Riyadh, a city undergoing rapid transformation within a desert context, this thesis aims to extend the applicability of urban regeneration theory and contribute to global discourse on sustainable urban development. Furthermore, this study aims to assess if green infrastructure, specifically green roofs and walls, can contribute to climate resilience in arid urban environments. This study can be divided into several objectives that relate to the environmental context of Riyadh, in the hopes of a broader application for similar arid regions. First, this research seeks to evaluate the urban landscape of Riyadh to identify areas where NbS can be feasibly integrated. This investigation will explore how these green infrastructure elements can be adapted to local conditions. Second, the study engages with urban regeneration theory, which emphasizes transforming urban spaces to improve resilience and sustainability. By applying this theory, the research examines how green infrastructure can be harmonized with Riyadh's urban landscape as to explore adaptive pathways that align NbS with evidence-based decision-making processes. Based on these goals, the following research question is proposed:

To what extent can green roofs and walls be applied to arid regions as robust climate mitigation solutions?

To answer the main research question, several sub-questions are defined:

1. What are the (perceived) barriers to and benefits of applying NbS in arid urban environments?
2. What are the methods and scenarios to assess the feasibility of implementing green roofs and walls in arid urban environments?
3. What are the perspectives of pivotal actors, and how can their views be incorporated into the pathways for implementing these solutions?

The first question seeks to explores the obstacles and potential advantages of implementing NbS, particularly in cities like Riyadh. It addresses the physical, economic, and meteorological factors that may either support or hinder the application of green roofs and walls in such environments. The second question seeks to clarify the methods and scenarios necessary for evaluating the practicality of these solutions. It will outline scenario-building techniques and potential pathways that consider current urban climate conditions. Finally, the last sub-question addresses the importance of stakeholder engagement in the implementation of green roofs and walls. It will investigate how insights from urban planners, engineers, and community members can shape adaptive pathways. This research focus specifically on UGI as a strategy for outdoor cooling.

While existing literature provides valuable insights into the general benefits of NbS, there is a significant gap concerning their application in arid urban environments. This research examines the evaluate the effectiveness of these systems in addressing challenges such as the Urban Heat Island (UHI) effect, but also strives to adapt urban regeneration theory to reflect the distinct socio-environmental characteristics of Riyadh. This study contributes to the growing body of knowledge on urban green infrastructure by addressing the established questions. It focuses on under-represented regions and offers practical insights into its adaptation to arid climates. The findings aim to inform sustainable urban planning policies and support the development of resilient cities in the face of climate change.

2

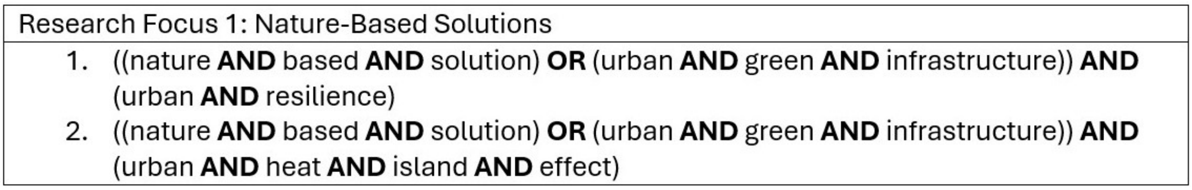
Literature Review

2.1. Search Strategy

The search strategy was initiated by examining the research question and identifying the core themes needed for research on the topic: Nature-based Solutions in general, the implementation of Urban Green Infrastructure in Arid Climates, Decision-making tools, and Microclimate Modelling. Based on these themes, several search queries were established, summarized through the logic gates below.

2.1.1. Research Focus 1

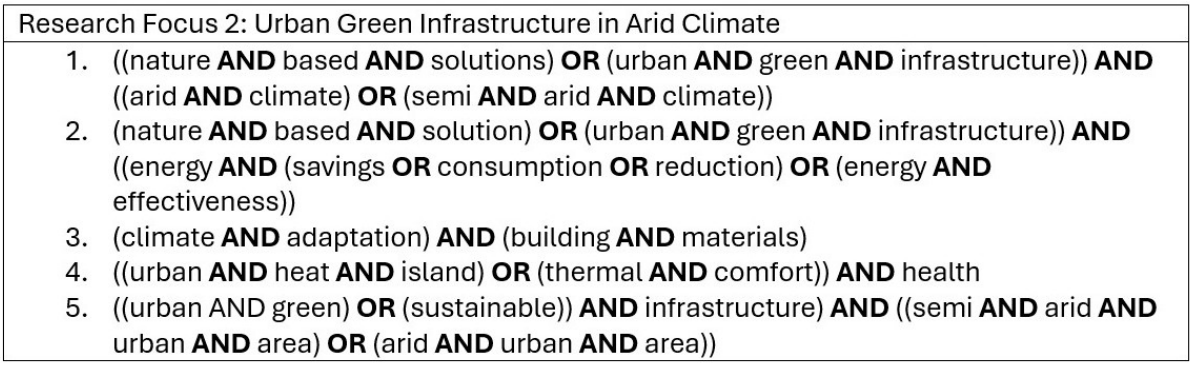
The primary aim of this research focus is to develop a comprehensive understanding of NbS and their potential applications in addressing urban and environmental challenges. This involves exploring the broader scope of NbS, including the options and tools available for their effective implementation. A key component of this focus is gaining deeper insights into the pathways that enable the successful integration of NbS into urban planning and policy frameworks. Additionally, the research focus seeks to investigate how NbS can mitigate the negative impacts of UHI, aiming to provide practical strategies and evidence-based recommendations for enhancing urban resilience and sustainability.



Research Focus 1: Nature-Based Solutions
1. ((nature **AND** based **AND** solution) **OR** (urban **AND** green **AND** infrastructure)) **AND** (urban **AND** resilience)
2. ((nature **AND** based **AND** solution) **OR** (urban **AND** green **AND** infrastructure)) **AND** (urban **AND** heat **AND** island **AND** effect)

2.1.2. Research Focus 2

This research focus looks into addressing the unique challenges associated with implementing NbS in arid climates. These regions face distinct environmental challenges that require a new and adapted approach to NbS design and application. A core objective is to understand the benefits and limitations of implementing NbS in arid environments, by recognizing the specific constraints imposed by factors such as water scarcity, extreme temperatures, and limited vegetation. An integral part of this exploration involves assessing how NbS can be adapted to suit the conditions of arid climates, but oftentimes rely on finding adjacent studies in semi-arid climates due to scarcity of research. This includes understanding what climate resilience and sustainability entail in these regions, as well as identifying tools to understand the needs of these ecosystems.

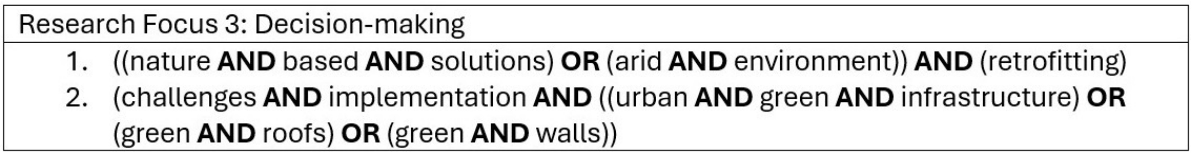


Research Focus 2: Urban Green Infrastructure in Arid Climate

1. ((nature **AND** based **AND** solutions) **OR** (urban **AND** green **AND** infrastructure)) **AND** ((arid **AND** climate) **OR** (semi **AND** arid **AND** climate))
2. (nature **AND** based **AND** solution) **OR** (urban **AND** green **AND** infrastructure)) **AND** ((energy **AND** (savings **OR** consumption **OR** reduction) **OR** (energy **AND** effectiveness))
3. (climate **AND** adaptation) **AND** (building **AND** materials)
4. ((urban **AND** heat **AND** island) **OR** (thermal **AND** comfort)) **AND** health
5. ((urban AND green) **OR** (sustainable)) **AND** infrastructure) **AND** ((semi **AND** arid **AND** urban **AND** area) **OR** (arid **AND** urban **AND** area))

2.1.3. Research Focus 3

This research focus explores the various of implementing NbS. To achieve this, frameworks, methods and strategies that enable successful integration of NbS into existing infrastructure have to be analysed. Additionally, the study seeks to define how successful implementation of NbS can be defined and measured.

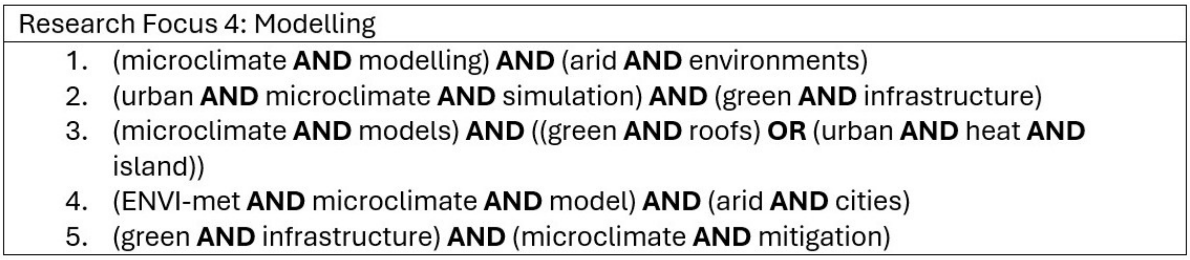


Research Focus 3: Decision-making

1. ((nature **AND** based **AND** solutions) **OR** (arid **AND** environment)) **AND** (retrofitting)
2. (challenges **AND** implementation **AND** ((urban **AND** green **AND** infrastructure) **OR** (green **AND** roofs) **OR** (green **AND** walls))

2.1.4. Research Focus 4

This research focus also seeks to explore microclimate modelling as an evaluation tool for UGI. By examining past research using microclimate modelling, the study aims to understand how microclimate modelling operates. This involves identifying and assessing examples of tools used in microclimate modelling, as well as scenario development and factors that need to be accounted for like extreme heat, low humidity, and limited water resources.



Research Focus 4: Modelling

1. (microclimate **AND** modelling) **AND** (arid **AND** environments)
2. (urban **AND** microclimate **AND** simulation) **AND** (green **AND** infrastructure)
3. (microclimate **AND** models) **AND** ((green **AND** roofs) **OR** (urban **AND** heat **AND** island))
4. (ENVI-met **AND** microclimate **AND** model) **AND** (arid **AND** cities)
5. (green **AND** infrastructure) **AND** (microclimate **AND** mitigation)

While the vast majority of the papers retrieved were recent, defined as published in the last 10 years, some dated back as far as 1984. While recency of publication did play a factor (particularly for innovative aspects of Urban Green Infrastructure) older articles were not disregarded when deemed relevant, as construction practices take time to evolve. Papers with relatively high numbers of publications were preferred. However, those with fewer citations were not excluded, because the topic remains largely unexplored and efforts were made to include research conducted in arid and semi-arid regions unless there was reason to believe the article contained serious flaws. This approach resulted in a body of work of over 70 papers. This search strategy allowed for a vigorous exploration of the topic, without steering away from the proposed research question. The literature was then recategorized into four new themes, the findings of which are described below.

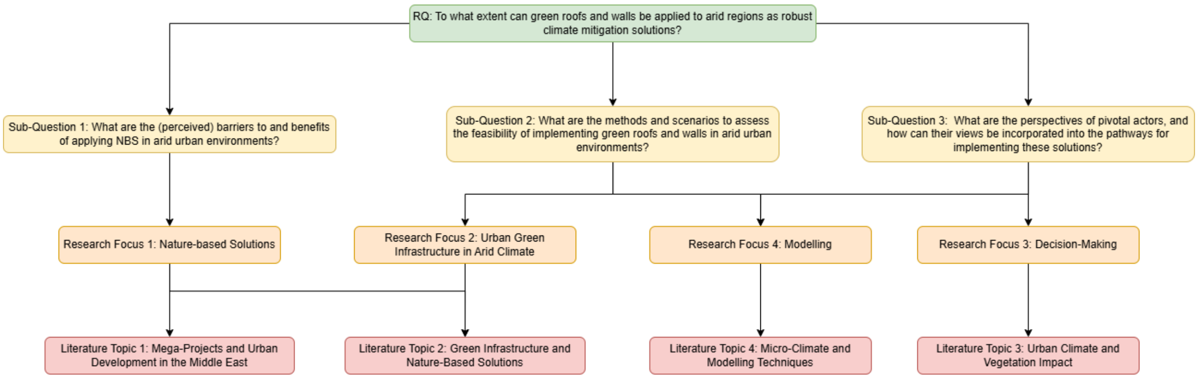


Figure 2.1: Relationship between the Research Question and the Literature Review

2.2. Mega-Projects and Urban Development in the Middle East

2.2.1. Development of Mega-Projects in the Middle East

Sources argue that the completion rate of mega-projects across the Middle East remains generally quite low despite much effort and considerable investments in them (Flyvbjerg , 2017; The trouble with megaprojects, 2023). Why many fail is speculated upon, but Flyvbjerg argues that the root cause always lies in psychology and power (Gerrand, 2023). According to Albogamy et al. (2013), studies reveal that 70% of public sector construction projects in the Middle East fail to meet their scheduled deadlines. Research conducted across Saudi Arabia and Jordan identifies several factors at play, including poor performance by lowest-bidder contractors under the tendering system, frequent design changes initiated by project owners, and insufficient early project planning. Conducting comprehensive research and developing a clear and resilient framework appears to be crucial. Furthermore, research indicates that liveability in fast-growing urban areas of emerging countries is severely under-investigated (Klingmann, 2022). This gap in research becomes particularly relevant when considering the predominant construction materials and methods used in countries like Saudi Arabia.

2.2.2. State-of-the-art in Saudi Construction

Citing prior articles, Wahl (2017) argues that in Saudi Arabia most residential buildings are constructed from concrete (81.9%), with brick or block houses making up 16.6%, while traditional mud or stone structures are rare due to the absence of regulations and standards for energy efficiency, along with limited economic incentives. This results in many buildings in the country lacking adequate insulation. This has a significant impact in the Gulf region, where high latitude and intense solar radiation contribute to substantial heat gain, particularly on the east and west walls during summer and on the south wall in winter. Wahl (2017) further argues that building materials and facade choices are also important in this hot, dry climate, and, once again citing previous articles, underlines that roofs should ideally be lightweight to minimize heat transfer and preferably of a lighter colour as to reflect more sunlight, as would reduce heat transfer into buildings. Once again referring to previous studies, Wahl (2017) reflects on window orientation, noting that it also influences daylighting and thermal comfort. South-facing windows are generally preferred, followed by east and west orientations, while north-facing windows are the least favourable due to minimal sunlight exposure. So far, shading devices such as window overhangs or shutters, are commonly used to mitigate solar radiation and lower cooling demands (Wahl, 2017). Because most buildings in Saudi Arabia have minimal insulation, basic wall construction methods were investigated. Research indicated that a simple wall structure typically includes an exterior concrete layer, followed by insulation, and an interior gypsum board (Diakaki et al., 2008).

2.2.3. Core Findings

In hot, dry climates, building materials and facade choices are critical for creating comfortable living spaces. Currently, the vast majority of residential buildings are constructed using concrete, which combined with poor insulation practices reduces energy efficiently drastically (Wahl, 2017). Window orientation further influences daylight and thermal comfort: south-facing windows are usually preferred, followed by east and west, while north-facing windows receive the least sunlight and are therefore less favoured (Wahl, 2017).

2.3. Green Infrastructure and Nature-Based Solutions

2.3.1. Modelling and Planning for Nature-Based Solutions

The principles of NBS are identified by Dorst and Raven (2019). These are "nature, as the concept's central foundation, may take many forms", "multifunctionality and a solution-orientation", "implementation through holistic and integrative governance and planning approaches" and "adaptation to place-based conditions" (Dorst & Raven, 2019). Van der Laarsen, in his 2023 thesis, argued that various models aid decision-makers in selecting suitable locations for NBS, predicting impacts, and understanding interactions. Citing Chang et al. (2021), he introduced the Green Infrastructure Spatial Planning (GISP) model, focusing on flood-based NBS in Taiwan. Van der Laarsen further argues that connectivity and interactions between different NBS are crucial but often overlooked and introduces the concept of using ecological network models to capture ecological flows, citing various sources. Yang and Wang (2017) introduce a Water Research and Forecasting model, which uses urban dynamics to "assess the potential water buffering capacity of urban green infrastructure in arid environments and its implications for sustainable urban planning" (Yang & Wang, 2017). This model can be used as a reference to assess the validity of irrigation system plans within the context of the urban expansion of Riyadh.

Bogis et al. (2018) addresses the challenges in retrofitting concrete channels into green channels in arid countries, focusing on the relationship between aridity, water resources, and irrigation needs for increasing green spaces. Recommendations include using cisterns for rainwater harvesting, separating grey and blackwater systems to reduce wastewater treatment infrastructure, converting concrete channels to green spaces to enhance public areas, attracting investment, improving walkability, and promoting biodiversity. Additionally, fostering relationships with academic researchers, conducting gentrification impact studies, involving landscape architects, and supporting sustainable practices are emphasized for effective implementation.

Bigurra-Alzati et al. (2020) performed a simulation using land-used based model to a semi-arid region of Brazil, which found that "green infrastructure strategies would reduce flooded areas and impacts". The study looks at three scenarios, the last one of which introduces green infrastructure as a variable, including rainwater interception on rooftops. This scenario shows a significant reduction in surface runoff and peak flow compared to the other scenarios. This study argues in favour of the green infrastructure as a solution to floods, but also as a solution to mitigate local scarcity issues. Catalano et al. (2021) discusses a framework that integrates Geographic Information Systems (GIS) and Building Information Modelling (BIM) to design urban spaces that enhance biodiversity and ecosystem services. This multidisciplinary approach allows for the simulation of different design scenarios, assessing their ecological impacts, and optimizing the layouts of urbanised spaces to support both human well-being and ecological stability. The approach emphasizes "eco-positive design", where urban development contributes to environmental sustainability and resilience. This review paper concludes that integrating nature into urban design is essential for enhancing biodiversity and ecosystem services. The article argues in favour of a multidisciplinary approach using GIS and BIM technologies to create eco-positive urban spaces that balance human needs with ecological health. The authors emphasize the importance of proactive urban planning and design strategies that contribute to sustainability and resilience, ultimately promoting a harmonious coexistence between urban development and natural ecosystems.

2.3.2. Understanding Urban Green Infrastructure and its requirements

Green roof technology involves the installation of vegetation on rooftops to reduce direct and diffuse radiation incidences. Mahmoud et.al (2017) argue that green roofs not only provide insulation, thus improving energy savings, but also moderate temperature fluctuations on the roof membrane, which in return reduce thermal stress and increases the membrane's lifespan. The study further argues that green roofs also affect relative humidity and offer various benefits including improved air quality, habitat creation, mitigation of the urban heat island effect, and reduced annual energy demand for buildings. In doing so they are expected to enhance thermal comfort, particularly in climates with high temperatures and solar irradiance (Mahmoud et.al, 2017). However, the same study finds that the performance of green roofs varies depending on the climate conditions, and the types of material used.

Raji et al. (2015) identify five common places to accommodate vegetation are : green roofs, green walls, green balcony, indoor sky garden, sky gardens. Focussing on their studies of green roofs and

walls, they indicate that they are recognized for their ability to reduce urban heat and improve energy efficiency, particularly in densely built urban areas. Green roofs, also known as horizontal greenery systems, can be divided into three types: extensive, semi-intensive, and intensive. Extensive green roofs (60-200mm, 60-150kg/m2) are cost-effective, low-maintenance solutions, and typically requiring no irrigation. They support hardy plants such as moss, sedum, herbs, and grasses, and are characterized by a shallow soil layer, making them ideal for ecological protection purposes. Semi-intensive green roofs (120-250mm, 120-200kg/m2), on the other hand, involve moderate costs and require periodic maintenance and irrigation. They can accommodate a wider variety of plants, including shrubs and grasses. Intensive green roofs (140-400mm, 180-500kg/m2) are the most maintenance-intensive and costly, resembling rooftop gardens with significant irrigation needs. The cooling effect of green roofs is largely attributed to evapotranspiration, which can release a significant amount of heat. Studies have demonstrated that green roofs can greatly reduce surface temperatures and heat flow, thus contributing to urban cooling. For instance, research by Permpituck and Namprakai indicates that increasing soil thickness from 10 to 20 cm can improve thermal performance, reducing heat transfer by up to 96% and energy use by up to 37% compared to bare roofs (Raji, Tenpierik, & van den Dobbelsteen, 2015).
Vertical greening systems, or green walls, can be direct or indirect facades, or modular systems. Direct and indirect green facades use climbing plants that grow directly on or near the building surface, while modular systems include continuous green walls, modular tray walls, and modular felt walls. Continuous green walls provide a uniform layer of vegetation, while modular tray and felt walls consist of pre-planted panels or modules that are attached to the building exterior. These modular systems allow for specific plant arrangements, either tailored to local climates and/or aesthetic preferences. Studies have shown that green walls, especially living wall systems, can reduce ambient air temperatures by up to 3.3°C near the wall, with shading effects extending to around 60 cm from it. In Mediterranean climates, green walls have been found to lower cooling demands during hot months, highlighting their energy-saving potential (Kontoleon & Eumorfopoulou, cited in Raji et al., 2015).
Despite their benefits, research on green roofs and walls in hot, arid regions remains limited. A systematic review by Seyam (2019) found that most studies by 2019 were conducted in countries like China and Spain, with few focusing on the Middle East or similar arid climates. Only a singular study was identified in the UAE, although more recent studies has emerged on green infrastructure in Qatar. These studies, however, are often limited to specific case studies, such as a single residential building in Qatar, highlighting the need for further investigation into the performance of green roofs and walls in extremely hot climates.

2.3.3. Infrastructure and Sustainable Urban Designs in (Semi-) Arid Urban Areas

Research by Anderson and Gouch (2021) addresses the productive application of green infrastructure on air pollution and carbon dioxide levels in Ontario, Canada, compared to non-productive application, demonstrating the importance of firsthand approaches to improve air quality and reduce greenhouse gas emissions. Additionally, Davies and Lafortezza (2019) argue that full adoption of Nature-Based Solutions cannot occur without a combination of reform which will lead to path dependency being broken, with poses as a major inhibitor for change. Research on the city of Tehran, a semi-arid city, reveals the importance of vegetation cover but also emphasizes the importance of variation in the green infrastructures to account for different local climate zones (Jamali et al., 2021). While these studies might not apply to Riyadh, inspiration can be drawn, particularly in the context of resilient infrastructure, greenhouse gas emissions mitigation and adapting to climate change. Additionally, the requirement for irrigation within cities with limited availability of water resources but growing population growth is explored through the case study of Phoenix, Arizona (United States). Modifications to the green infrastructure and irrigation practices in Phoenix have a significant impact on the city's thermal environment, particularly upon the implementation of water-saving xeriscaping (Yang & Wang, 2017). However, urban ambient temperature increased by approximately 1 °C as a result of these practices.
The use of white- or light- coloured walls is a method commonly adopted in several regions to leverage the reflectivity of white walls as a passive cooling strategy to improve energy efficiency and thermal comfort in buildings. Paolini et al. (2017) note that this method is particularly popular in Mediterranean countries, as well as Middle Eastern countries (such as Turkey, Egypt and Morocco) where they are commonly used on traditional architecture (El-Gayar et al., 2014). Other literature mentioned Southern United States (such as Arizona and New Mexico), where bright-coloured walls are used to leverage the 'thermal flywheel effect' of large walls (Duffin & Knowles, 1984), Australia (Razzaghmanesh, 2017) and

China (Sun et al., 2015). While many benefits can be noted for the energy performance of the building itself, studies assessing the benefits of it on a larger scale are lacking. White coating is known to adjust several properties of concrete. First, it reduces heat absorption, which in turn increases reflectivity (Al-Sanae et al., 2013; El-Gayar et al., 2014; Li et al., 2021). Then it slightly lowers emissivity compared to concrete with no coating (Mukherjee, 1992). Other parameters such as thermal conductivity, specific heat and thermal transmittance do not seem to be affected by a light-coloured coating.

2.3.4. Ecological Transitions and Green Infrastructure in Riyadh

Converting traditional roofs to green roofs in Saudi Arabia is an environmentally preferred option that meets thermal conductivity standards and suits the region's arid climate (Alqahtany, 2022). However, despite calls to adopt sustainable strategies like green roofs, there has been significant delay in implementation compared to other countries (Alqahtany, 2022). One underlying reason could be that the fragmentation of green spaces in Riyadh is culturally influenced (Sposito & Scalisi, 2023), making city-wide implementation difficult. Guidelines for ecological transitions include strengthening wadis as connection infrastructure, peri-urban parks, and soil demineralization. The existing green spaces often adopt unsustainable Western models, highlighting the need for more sustainable approaches removed from traditional Western methods (Sposito & Scalisi, 2023).

The use of windcatchers, Qanats and other historical and culturally relevant traditional engineering solutions in the context of modern architecture within arid climate conditions are explored as a potential solution for sustainable urban design. Nejat (2018) argues that “in hot arid climate, 60% of total building energy consumption in this area is associated with cooling systems” and notes that natural ventilation can be achieved by using traditional building techniques, such as windcatchers, helping reduce CO_2 emissions. This research distinguishes diverse types of windcatchers, suitable for several types of arid conditions (Nejat, 2018). Moreover, water scarcity can also be addressed by turning to such traditional engineering methods (such as water tunnelling systems called Qanat). Such systems were developed to extract groundwater for domestic (and agricultural) use in desertic conditions, but their use has since diminished (Taghavi-Jeloudar et al., 2013). Taghavi-Jeloudar et al. (2013) recommends using novel materials, such as Geotextile pipes and Geomembrane materials, to develop new Qanat systems when possible. However, engineers at the Saudi-based firm Egis have noted that the implementation of such traditional methods are not always economically.

2.3.5. Core Findings

Retrofitting concrete structures with green solutions can be challenging in arid regions. NbS, which emphasize ’eco-positive design’ (Bigurra-Alzati et al., 2020), show that the introduction of vegetation into urban infrastructure not only enhances biodiversity and ecosystem services but also strengthens environmental resilience. Research on green roofs, for example, highlights their ability to improve energy efficiency by providing insulation. Such roofs also reduce temperature extremes through evapotranspiration, extending the lifespan of the roofing materials. However, the performance of green roofs varies significantly depending on local climate conditions and the materials used.

Vegetation can be incorporated in several ways: green roofs, green walls, green balconies, as well as indoor and outdoor sky gardens. Among these, green roofs and green walls have gained particular recognition for their ability to mitigate urban heat in densely built areas (Raji et al., 2015). They typically fall into three categories: extensive (low cost, minimal maintenance), semi-intensive, and intensive (higher cost, more maintenance, but better performance). Additionally, literature points out the distinctive lack of quantitative research conducted on the effects of such techniques in arid climates (Seyam, 2019).

Despite the proven benefits, implementing NBS often requires structural reforms that break existing patterns of urban development. Meanwhile, using white or light-coloured walls has become a popular passive cooling method in Mediterranean and Middle Eastern countries (e.g., Turkey, Egypt, Morocco), as well as in parts of the United States (Arizona and New Mexico), Australia, and China (Duffin & Knowles, 1984; El-Gayar et al., 2014; Paolini et al., 2017; Razzaghmanesh, 2017; Sun et al., 2015). Light-coloured finishes improve energy efficiency by reflecting more sunlight and slightly reducing emissivity, though they do not significantly alter other thermal properties such as conductivity or specific heat.

In Saudi Arabia, converting conventional roofs to green roofs meets local thermal conductivity standards and aligns well with the arid climate (Alqahtany, 2022). However, progress has been slower than in other countries, partly due to the cultural fragmentation of green spaces (Sposito & Scalisi, 2023)) which makes large-scale adoption more difficult. Ecological transition strategies in the region include reinforcing wadis as connective infrastructure, developing peri-urban parks, and prioritizing soil demineralization. Together, these measures, ranging from white walls to green roofs, demonstrate how innovative design and strategic planning can move arid cities toward more sustainable, resilient urban environments.

2.4. Urban Climate and Vegetation Impact

2.4.1. Effectivity of Urban Vegetation Cover

In their dated, but insightful 2003 paper, Wong et al. found that green roof systems are considerable cheaper than traditional thermal and waterproofing roof treatments. Additionally, further literature finds that green roofs are highly effective at reducing energy consumption (Perini & Rosasco, 2016; Coma et al., 2018). Citing various authors, Alqahtany (2022) argues that “the energy consumption reduction values turned out to be between 6.5 and 17% for a case study in Guangzhou, China, a four-story representative building in Amman, Jordan, and a three-story building in Iran” and that “green roofs could reduce the cooling requirement by 6% in the summer for an eight-story residential building”. Mahmoud et al. (2017) found that research in Hong Kong’s warm but humid climate found significant energy reductions with sedum plants. In Jordan, green roofs reduced HVAC energy consumption by 17%, whereas studies in Egypt showed annual energy savings between 15% and 32%, depending on soil thickness and thermal conductivity (Mahmoud et.al, 2017). Green roofs also reduced surface temperatures by up to 20°C compared to conventional roofs (Mahmoud et.al, 2017). Furthermore, simulations in Singapore indicated a reduction of surface temperature by 7.3°C and a decrease in ambient air temperature by 0.5°C during the day (Mahmoud et.al, 2017). Moreover, green facades in Singapore have demonstrated a notable reduction in radiation levels measured on building surfaces (Chow & Bakar, 2017), thus decreasing the heat experienced inside these buildings. This is particularly relevant to the case of Saudi Arabia as it is believed that 70% of the total electricity consumption within buildings are a result of cooling efforts (Khabaz, 2018). Additionally, green vegetation is said to increase the longevity of by 20 years due to its protective nature (Clark et al. 2004), as well as reduce sound exposure within and around concerned buildings (van Renterghem, 2005). Kraemer & Kabisch (2022), in a study conducted in Germany, found that spaces which are tree-dominated maintain cooling effects even under extreme heat and drought, and are more effective during peak temperatures than grass-dominated areas. Reu Junqueira et al. (2021) argue that green infrastructure can be effective at mitigating urban climate change impacts, such as flooding, by managing water flows and alleviating pressure on stormwater systems. Additionally, vegetation provides benefits such as thermal comfort. Unlike traditional stormwater strategies, green infrastructure focuses on managing at the source. Furthermore, harvesting rainwater on rooftops appears as a cost-effective conservation measure that reduces runoff and sewage discharge (Bigurra-Alzati, 2020). The previous study, based in Mexico, focused on rainfall with a 75% exceedance probability (86% of annual rainfall) to determine minimum water storage needs. The study finds that rainwater collection from 60 m^2 rooftops can replace 1.07-2.04 m^3/month of domestic consumption, improving water security and mitigating shortages. Green infrastructure, such as infiltration trenches and bioretention systems, are recommended by the authors to enhance stormwater capture and restore predevelopment hydrology in semi-arid areas. Combining rainwater harvesting and green infrastructure would thus efficiently manage urban runoff and prevent flooding.

2.4.2. Urban Heat Island Effects in Riyadh and Ecological Footprint in Saudi Arabia

In Saudi Arabia, most buildings use reinforced concrete for roofs, which is inefficient due to high thermal conductivity, leading to 70% of electricity consumption being used for air conditioning (Alqahtany, 2022). The same study, citing several prior research, highlight the need to redesign roofs to improve thermal efficiency, using modern methods like steel fibber reinforced concrete. Furthermore, the residential sector’s energy consumption is increasing with the population growth of 2.5% per year, resulting in the

increase of already high CO_2 emissions due to the climate's cooling and heating demands (Alqahtany, 2022).
Moreover, unsustainable mobility in Riyadh is addressed through the construction of a new public transportation network aligned with Saudi Vision 2030 goals (Sultan et al., 2021,), in an attempt to steer away from car-dominated infrastructures to improve the quality of life of its residents. Furthermore, a study on the city of Riyadh demonstrates the intertwining of social and economic reforms with sustainable urban planning. Analyses point to a gap in adopting financially inclusive models, neglecting low-income families (Klingmann, 2022). The Urban Heat Island phenomenon, notable and heavily urbanized areas, has negative impacts on health and quality of life (Imam, 2023). Despite the initial efforts of scientists involved in the Green Riyadh Project, a decline in vegetation areas and an unexpected increase in Land Surface Temperature (LST) values can be noted, suggesting a need for a review of urban materials and planning strategies. Indeed, research suggests that the selected plant species were not well-adapted to Riyadh's environment, 'resulting in a lack of sustainability' (Imam, 2023). As such, this suggests the importance of adapting green infrastructure to the local environment.

2.4.3. Outdoor temperatures and Thermoneutral Comfort

The thermoneutral zone describes a temperature range where a person can maintain a stable body temperature without expending extra energy. For a clothed human, this range extends from 14.8°C to 24.5°C, as shown by Kingma et al. (2012). Typically, the optimal conditions for a resting person fall within 20°C to 25°C with low wind and moderate humidity levels (University of Arizona, 2012). Studies on outdoor thermal comfort and the thermoneutral zone provide information into how environmental factors like temperature, solar radiation, and wind influence human comfort levels. For example, a study by Yang et al. (2013) in Singapore identified that the neutral outdoor operative temperature, where people felt comfortable, was around 28.7°C, with a slightly lower preferred temperature of 26.5°C (Yang et al., 2013). While radiation is often the most influential factor in thermal comfort, wind speed can also play a role, particularly in temperate climates, but also physiological factors, such as weight and skin tones (Yang et al., 2013).

2.4.4. Core Findings

Green roofs are often seen as a cost-effective alternative to traditional thermal and waterproofing treatments, with studies suggesting they can cut energy consumption by anywhere from 6% to 32%, depending on the specific location and conditions (Alqahtany, 2022; Mahmoud et al., 2017). They also contribute to lowering both surface and ambient air temperatures. Singapore, for instance, reports decreases of up to 0.5°C in ambient temperatures where green roof systems have been adopted.

In Saudi Arabia, reinforced concrete remains a common roofing material, yet its high thermal conductivity pushes air conditioning to consume around 70% of the country's electricity (Alqahtany, 2022). Rapid population growth of approximately 2.5% per year further exacerbates energy demands, driving up already high CO_2 emissions (Alqahtany, 2022). Although initiatives like the Green Riyadh Project initially aimed to expand vegetation cover, they have unfortunately witnessed a decline in green spaces and a spike in Land Surface Temperature (LST). One key issue was the choice of plant species, which were not suited to Riyadh's climate (Imam, 2023). As average temperatures in the Middle East regularly surpass the comfortable range of 15°C to 29°C (Kingma et al., 2012; University of Arizona, 2012; Yang et al., 2013), these findings underscore the need to reevaluate urban materials and planning strategies for enhanced sustainability and climate resilience.

2.5. Micro-Climate and Modelling Techniques

A study from Algeria explored the role of UGI in reducing UHI at the Urban Canopy Layer (UCL) level. Using Landsat 8 data from the hottest period of the year, the research measured Land Surface Temperature (LST) and correlated it with vegetation information as provided by NDVI and NDBI. The research found that in area with a slightly higher GR/UGI ratios, LST was at time significantly lower. This suggests that urban green infrastructure can help create Urban Cool Islands (UCI) even in semi-arid climates. Hotspots were selected based on tall buildings with bitumen-flat roofs, which lacked natural shading. The study concluded that a GR/UGI ratio increase of 0.0063 could result in a temperature drop of 1.24°C, indicating the cooling potential of even modest amounts of green infrastructure (Sahnoune & Benhassine, 2017).

Another Algerian study conducted a techno-economic analysis on green walls in extreme climates. While vegetation has historically been used on buildings in colder regions for insulation and cooling, this is less common in hot areas. The study evaluated three scenarios: green façades, living walls, and vegetated roofs, utilizing the ENVI-met software to simulate retrofitting options on a 75m2 house. The results indicated that green walls and roofs could lower local temperatures by 2 to 3°C. While intensive green roofs offered greater cooling, extensive green roofs were recommended for their cost-effectiveness in dense urban areas due to lower maintenance and construction costs (Benoudjafer, Laoufi, & Benoudjafer, 2022).

A study from Egypt focused on energy savings from green roofs in various urban densities, using DesignBuilder software for detailed building simulations. The study modelled a hypothetical residential tower of varying heights (5, 10 and 15 floors, all 260m2) and analysed the effects of extensive and intensive green roofs under Cairo's climate conditions. Results showed that extensive green roofs can be effective at reducing cooling energy demand in buildings up to 30 meters high (15 floors), particularly if located in dense urban areas. Although intensive green roofs provided more significant temperature reductions and improved outdoor thermal comfort, they were less cost-effective compared to extensive green roofs (Aboelata, 2020).

Finally, a study from Qatar assessed green roofs and walls as climate change mitigation tools in an extremely hot and dry climate. Using the CCWorldWeatherGen Tool to project future climate scenarios, and modelling with EnergyPlus and DesignBuilder, the study analysed various retrofitting options on a singular mansion, including enhanced insulation and the installation of green walls and roofs. Results indicated that enhanced insulation and triple-glazed windows were more efficient at reducing energy consumption than green roofs, which, in Qatar's climate, require substantial irrigation. The requirement for desalinated water, due to the region's limited freshwater, further increased the environmental impact of green roofs and walls, as sustaining these systems would require significant energy input (Andric, Kamal, & Al-Ghamdi, 2020).

2.5.1. Core Findings

Multiple studies across North Africa and the Middle East highlight the effectiveness of green retrofitting options. In Algeria, one study used Landsat 8 data to measure Land Surface Temperature (LST) during the hottest period and correlated those findings with vegetation coverage (Sahnoune & Benhassine, 2017). Another Algerian study then simulated three retrofitting scenarios (green façades, living walls, and vegetated roofs) on a small house using GIS and ENVI-met software (Benoudjafer, Laoufi, & Benoudjafer, 2022). In Egypt, researchers modelled a hypothetical residential tower under Cairo's climate conditions, evaluating how both extensive and intensive green roofs perform at different building heights (Aboelata, 2020). Finally, in Qatar, a study focused on a single mansion and explored upgrades such as improved insulation and the installation of green walls and roofs, underscoring how these interventions can help mitigate heat in arid environments (Andric, Kamal, & Al-Ghamdi, 2020).

3

Methodology

3.1. Field Work

This thesis involved a two-week exploratory trip to Riyadh, to gain a first-hand understanding of the city's architectural styles, urban divisions, lifestyle and aesthetic preferences. Prior to the trip, a tentative itinerary was developed based on desk research, highlighting key locations that offered insights into Riyadh's urban structure and potential for green infrastructure. This itinerary included a range of sites, such as malls, prominent buildings, cultural landmarks, road networks, and various locations where Egis had been involved in infrastructure development.

3.1.1. Fieldwork Preparation

The research began by setting key objectives for the fieldwork. The main aim was to explore the various building types and architectural styles in Riyadh, along with significant landmarks, local vegetation, sand, and existing UGI. To get a complete view of the city's landscape, a preliminary itinerary was created using various travel resources. These included online platforms like Reddit, Quora, and TripAdvisor, as well as trusted travel guides such as Visit Saudi, Condé Nast Traveller Middle East, and Expedia. Expat-focused resources like Insured Nomads and InterNations were also used for local insights. Special focus was placed on third spaces like parks and malls to understand potential areas for UGI integration.

3.1.2. Exploration

During the visit, malls were important urban spaces, especially in residential areas, often serving as ”third spaces” for public life. Due to their role and potential for green architecture, several malls were studied closely. Key sites visited during the exploration included:

- **Ministry of Rural Affairs:** A micro-example of ongoing reforestation efforts.
- **Ministry of Interior:** Showcasing examples of green walls in urban design.
- **Kingdom Tower:** The tallest structure in Riyadh, offering panoramic views of the cityscape.
- **Boulevard Riyadh Mall, Roshn Front Shopping Mall, Via Riyadh, and Centria Mall:** All examples of aesthetically integrated urban green infrastructure.
- **Salam Park:** Observed for its plant species and landscaping relevant to Riyadh's green initiatives.
- **King Fahd Road:** An example of urban green walls lining a major thoroughfare.
- **Diriyah and Royal Commission of Riyadh City Headquarters:** Sites exemplifying traditional architectural elements.
- **Bodeker Architects Bureau:** A micro-nursery visited for its innovative approach to plant care in urban environments.

This field trip was essential for understanding Riyadh's layout and the current use of green infrastructure in areas like commercial centers and public spaces. Observations from the trip directly supported

the analysis of how green infrastructure could be expanded in the city. A key part of the trip was assessing the main architectural styles, materials used, and the overall structure of Riyadh. This helped in understanding both the practical and aesthetic aspects of the city's development, which is important for incorporating green infrastructure in a way that complements existing designs.
During the visits, particular attention was given to:

- **City Structure:** The city's sprawling design is shaped by expansive road networks, modelled after U.S. cities, through grids. A feature of Riyadh's structure is the prevalence of large commercial hubs (malls), which serve as focal points for public life. These hubs are often in the proximity of residential areas. Understanding this city structure was vital for identifying potential locations for future green infrastructure projects that could benefit both densely populated and emerging districts.
- **Architectural Styles:** Traditional Saudi architecture, referred to as Najdi or Vernacular architecture, is most often seen in historical sites such as Diriyah, was contrasted with modern, sleek designs found in newer commercial and residential developments, or concrete complexes found in older developments. The balance between these three styles was of particular interest, as it demonstrated Riyadh's evolving urban identity.
- **Materials Used:** Commonly used materials, including concrete, glass, and steel, were observed in various buildings. In contrast, older, more traditional sites, or new build referencing such sites, often incorporated adobe and stone, reflecting Riyadh's cultural heritage. The materials chosen in each context do not always reflect functional purposes, such as thermal efficiency, durability, and alignment with the region's climate.
- **Aesthetic Purposes:** Many modern buildings, like malls and ministries, use sleek, simple styles with lots of glass, bringing in natural light. This contrasted with more traditional buildings, which have detailed facades with earthy colours, rooted in the city's cultural heritage. Although Riyadh mostly feels like a big network of highways with few public or green spaces, newer buildings are making an effort to include green architecture and lighter, supporting urban beautification and creating memorable landmarks.

3.2. Interview

3.2.1. Expert Interviews Preparation

The second phase of the research trip to Riyadh involved conducting interviews with professionals specializing in vegetation, irrigation, infrastructure, urbanization, floodrisk, and urban heat island (UHI) effects (table C.1, Appendix C). These interviews aimed to gather in-depth information and expand the understanding of Riyadh's unique climate and the related challenges. The interviews were semi-structured, allowing experts the flexibility to share their professional insights into the structural, ecological, and policy dimensions of green infrastructure. Although the questions were developed beforehand (Appendix B), the experts were selected through networking upon arrival at Egis in Riyadh, to ensure relevance and expertise. The experts were contacted through personal contacts, starting with a first contact person and snowballing. Experts were identified throughout the first week of the trip (between April 19th and April 26th 2024) and various interview dates were set up for the same week and the following week. Upon recommendation from other interviewees, two experts were approached without prior notice, compelling them to grant an unscheduled interview. Before going forward with the interviews, questions and interview methodology had to be approved by the ethics committee of the associated university (Appendix A). An iterative process was used to refine the key questions, aligning them with TU Delft's ethics guidelines to guarantee complete anonymity. This approach encouraged open and candid responses from the experts. The objectives of the interviews were twofold: first, to build a comprehensive understanding of the core issues surrounding Riyadh's climate; second, to gauge expert opinions on what they considered feasible and infeasible solutions to these challenges, helping to steer further research. Experts would be chosen based on their specific knowledge relevant to the research. The interview questions were divided into general and expert-specific sections, with each session designed to last no more than 45 minutes. To stay focused, questions were grouped into six main themes:

1. Vegetation & Plant Requirements in arid environments.

2. Green Infrastructure Implementation, looking at challenges and benefits.
3. Climate and Urban Heat Island (UHI) Mitigation through vegetation and UGI
4. Water & Irrigation Systems, exploring methods for sustaining green infrastructure.
5. Flood Risk & Stormwater Management, considering green roofs and walls.
6. Urban Planning & Policy Integration, with emphasis on alignment with Saudi Vision 2030

3.2.2. Operation

These semi-structured interviews were flexible, allowing experts to share their insights freely while still covering core topics. The participants were sampled based on topic, and selected for the interviews by initially identifying a key individual whose expertise aligned with one of my six themes (C.1, Appendix C). Following each interview, participants were asked to refer others with relevant expertise in the remaining themes. This snowball sampling approach ensured a targeted selection of experts across all topics. All interviews were recorded for accurate transcription, with strict anonymity maintained to protect participants' privacy.

The interviews aimed to address key issues such as the decline of vegetation in arid climates, the suitability of different plant species, and the challenges and benefits of implementing green infrastructure in Riyadh. Additionally, they examined the role of vegetation in reducing the Urban Heat Island (UHI) effect, assessed the irrigation and water systems needed for UGI sustainability, and explored how green roofs and walls could help with flood risk and stormwater management. The data from the interviews were analysed through thematic analysis using a reflexive approach. The interviews were thus coded for recurring themes as to identify which patterns, concepts, key words, and (explicit and implicit) meanings came up more often (table F.1, Appendix C). The emerging common themes were divided into Open Code and Axial Code. Interviews ranged from 7 to 31 minutes, with an average duration of 20 minutes. Each expert was initially intended to be asked between five and seven questions, separated into general questions common to all interviewees, and others specific expertise. However, due to time constraints, some experts were only asked three targeted questions.

3.3. Remote Sensing

3.3.1. Remote Sensing for Vegetation and Land Surface Temperature (LST) Preparation

For this research, remote sensing was used to gather a greater understanding to the climate variation in region of Riyadh. To complete the data obtained through Egis, open-source data regarding vegetation and surface temperature had to be gathered through EarthExplorer. Data provided by Egis included land-use (buildings), valleys and detailed vegetation cover.

To perform remote sensing, a trusted and widely used method was chosen based on well-known scientific studies. A key reference was J.A. Sobrino et al. (2004), whose work on calculating Land Surface Temperature (LST) with LANDSAT data has over 2,700 citations. This method gave a reliable basis for using ArcGIS Pro and USGS Landsat images.

Search terms like “Land surface temperature + LANDSAT” and “LST LANDSAT CALCULATION” were used to find this study and other useful sources, ensuring the analysis was accurate and well-supported.

3.3.2. Data Acquisition

For this research, remote sensing data were obtained through the EarthExplorer platform provided by the USGS (United States Geological Survey). The study uses Landsat 8 satellite imagery, particularly **Band 4 (NIR - Near Infrared), Band 5 (RED), and Band 10 (TIRS - Thermal Infrared Sensor)**. The chosen dates were August 18, 2023 (for East Riyadh) and August 25, 2023 (for West Riyadh), with both images captured at 7 AM local time. Information about the images selected for remote sensing, such as file name, location and acquisition information, can be retrieved in Appendix D.

Satellite images from August were selected for this study because it is the hottest month of the year in Riyadh. According to Statista, August consistently records the highest maximum temperatures, averaging around 44°C. During August, the city experiences peak temperatures, making it an ideal period for analysing the Urban Heat Island (UHI) effect and identifying areas where green infrastructure could provide the most significant cooling benefits.

3.3.3. Cloud Interference Assessment

Before processing, the images were manually checked for cloud interference. This was done by verifying the properties of the selected image, and verifying that the cloud cover was numerically low. In the case of this research, the image selected had a cloud cover of 0%. Assessment of the images in EarthExplorer ensured that cloud cover was minimal and would not distort the results of the vegetation and land-use analysis.

3.3.4. Image Processing

The two images from East and West Riyadh were merged in ArcGIS Pro to create a unified spatial dataset of the city. This allowed for a comprehensive analysis across different regions of Riyadh, facilitating comparisons of vegetation, land-use patterns, and valleys.

3.3.5. Vegetation Analysis: NDVI Calculation

Vegetation data were provided by the engineering firm. Additionally, vegetation analysis was conducted using the Normalized Difference Vegetation Index (NDVI), which quantifies greenness in satellite images. NDVI was calculated using the following formula:

$$\text{NDVI} = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}}$$

Where:

- NIR refers to Band 4 (Near-Infrared),
- RED refers to Band 5 (Red band).

The resulting NDVI map provided a colour gradient representing vegetation health, with greener areas indicating healthy vegetation and darker areas representing lower vegetation or bare soil.

3.3.6. Land-Use and Valleys Data

In addition to the NDVI analysis, land-use and valleys data were provided by Egis. This data was essential in identifying the urban distribution of developed areas, as well as the natural reliefs.

3.3.7. Land Surface Temperature (LST) Mapping: Mono-Window Algorithm

To map the land surface temperature (LST), a simplified Mono-Window Algorithm, as described in Sobrino et al. (2004) and Avdan and Jovanovska (2016), was applied using Band 4, 5 and 10 from Landsat 8. The LST was calculated using the following steps in ArcGIS Pro. Constant values can be found in the Landsat Meta file, which can also be downloaded from the USGS opensource website.

1. **Convert Digital Numbers (DN) to Radiance:**
   The purpose of this step is to convert the data captured by satellite. This data is often given in a format called digital numbers, but need to be converted to radiance to obtain the thermal spectrum. Using the Raster Calculator, Band 10 digital numbers were converted to radiance:

   $$L_\lambda = M_L \cdot Q_{\text{cal}} + A_L + O_i$$

   Where:

   - L_λ is the spectral radiance,
   - M_L is the band-specific multiplicative rescaling factor (equal to 0.000342),
   - Q_{cal} is the Band 10 image,
   - A_L is the band-specific additive rescaling factor (equal to 0.1),
   - O_i is the correction for Band 10 (equal to 0.29).

2. **Convert Radiance to Brightness Temperature:**
In this step, the Planck equation is used to convert the previously obtained radiance into temperature as to assess the surface temperature of a specific region. The radiance was then converted into brightness temperature using the formula:

$$\text{BT} = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)} - 273.15$$

Where:

   - BT is the brightness temperature in Celsius,
   - K_1 and K_2 are thermal constants specific to the Landsat 8 sensor (equal to 1321.08 K and 777.89 K, respectively).

3. **Calculating the Proportion of Vegetation:**
Using the previously established NDVI map, the proportion of vegetation P_v can be calculated, to establish what the vegetation cover is.

$$P_v = \left(\frac{\text{NDVI} - \text{NDVI}_{\text{min}}}{\text{NDVI}_{\text{max}} - \text{NDVI}_{\text{min}}}\right)^2$$

Where:

   - NDVI_{min} is the NDVI value for soil (determined to be -0.21152),
   - NDVI_{max} is the value for the tallest vegetation (determined to be 0.504528).

4. **Calculate the Land Surface Emissivity:**
The previous steps assume that the surface behaves as a blackbody. This step accounts for the actual energy emitted by this surface, which does not behave as a blackbody. Emissivity ranges from 0 to 1. Vegetation has a high emissivity, while soil has a lower emissivity. To calculate the ground emissivity, the following equation applies:

$$\varepsilon = \varepsilon_V \cdot P_v + \varepsilon_s \cdot (1 - P_v) + C$$

Which can be reduced to:

$$\varepsilon = 0.004P_v + 0.986$$

Where:

   - ε_V is the vegetation emissivity,
   - ε_s is the soil emissivity,
   - C is the surface roughness. A homogenous or flat surface has a value of $C = 0$.

5. **Retrieve Land Surface Temperature:**
Finally, the land surface temperature (LST) can be retrieved by superimposing the previously generated maps, using the following formula:

$$T_s = \frac{\text{BT}}{1 + \left(\frac{\lambda \cdot \text{BT}}{\rho} \ln \varepsilon\right)}$$

Where:

   - $\rho = 1.438 \times 10^{-2}$ m K,
   - λ is the average limiting wavelength (equal to 10.895 for Landsat 8, Band 10).

3.3.8. Colour Gradient and Temperature Range

The final LST map was visualized using a colour gradient, where red and orange represented higher surface temperatures (ranging from 40°C to 55°C), and blue and green indicated cooler temperatures (ranging from 25°C to 40°C). This gradient helped to easily identify the hottest zones in Riyadh, which corresponded to high-density urban areas with minimal vegetation and little shading.

3.3.9. Combined Analysis

The NDVI and LST maps were overlaid with the land-use and valleys data to examine the interaction between vegetation, urban infrastructure, and natural features. This combined analysis enabled the identification of regions where green infrastructure could mitigate the urban heat island (UHI) effect, to enhance the microclimate in line with Riyadh's sustainable urban development goals.

3.4. Microclimate Model

3.4.1. Microclimate Modelling Preparation

The model design draws inspiration from methods used in earlier studies conducted in the Middle East and North Africa, including Algeria, Egypt, and Qatar. These studies are reviewed in Chapter 2.4. Although the referenced research varies in goals and scale, their methods provided adaptable techniques, restructured and tailored to fit the objectives of this study. This research combines, truncates and revises these methods to create a new approach.

Sahnoune and Benhassine (2017) used Landsat 8 data to study LST in a residential area of Constantine, Algeria. A similar method was applied here to provide an initial LST overview. Their use of ENVI-met, although used to simulate green roof models for energy use and greenhouse gas emissions, also guided the selection of the software as a tool. Laoufi and Benoudjafer (2022) also used ENVI-met, this time to simulate green walls and roofs on a small house in Algeria, assessing the thermal effects of vegetation on the building's surface. While their study informed the methodology, ENVI-met was adapted in this thesis to focus on ambient air temperature of the surrounding instead. Aboelata (2020) analysed the impact of green roofs on energy consumption in Cairo using DesignBuilder, varying building heights to determine which structures achieved the greatest impact. Finally, Andric, Kamal, and Al-Ghamdi (2020) modelled future climate scenarios in Qatar, exploring retrofitting options like improved insulation and green roofs using EnergyPlus and DesignBuilder. Both these work inspired the use of diverse retrofitting strategies and scenario analysis in this study.

3.4.2. Conceptualisation

The aim of this model is to recreate a small part of the city to study how building facades impact their surroundings. Insights from interviews helped set up different scenarios that show possible variations: green roofs (GR), green walls (GW), a combination of both (GR/GW), and white walls.

Figure 3.1: Outline of the District Al Malaz. *Google Earth.*

Field research and satellite images were used to identify common infrastructure types and patterns in the area, while literature was referenced to understand typical building structures and materials. A key part of this analysis is to see if combining green roofs and walls might strengthen their cooling effects. Additionally, the study looks at white walls, which reflect sunlight, to check if they could be an effective cooling tool for the buildings surroundings or if they might increase street temperatures by reflecting sunlight onto them. The microclimate modelling for this study was conducted using ENVI-met, a science-based tool that simulates surface-plant-air interactions within urban environments. A basic digital model of a group of houses in the selected area was created, incorporating the main structure, construction and material while leaving out finer and more intricate elements. The model replicates the physical environment, allowing for the simulation and analysis of the climate conditions on the proposed infrastructure.

The district of Al Malaz (figure 3.1) was chosen for its diversity, encompassing both commercial and residential areas. Spatial analysis was performed using satellite imagery from Google Earth to assess the geometry and layout of the district. To gain a more detailed understanding of the area's urban design, the most frequent building types were analysed through fieldwork and Google Street View. These buildings are typically 2-3 story, square-shaped structures, arranged in a grid layout with four houses horizontally and two vertically per block. The streets surrounding these blocks were also studied. Based on existing research, a standard story height of 9 m was used for the model, corresponding to 6-9 m for 2-story buildings and 9-12 m for 3-story buildings. Estimates of building and street dimensions were derived from 10 measurements taken both vertically and perpendicularly for streets, and 10 housing blocks were measured in the same manner. A housing block was defined as four houses horizontally and two vertically, all attached to one another. The length and width of a house were both set at 25 m (adding to 625 m²), and each housing block covered an area of 100 m x 50 m. Streets were measured at 20m wide for west-to-east roads (horizontally) and 15 m wide for north-to-south roads (vertically). The total surface of a singular house is 25x25x9 (L x W x H) (figure 3.2). In Appendix E, the exact measurements used for the averages can be found in figures E.2 and E.3.

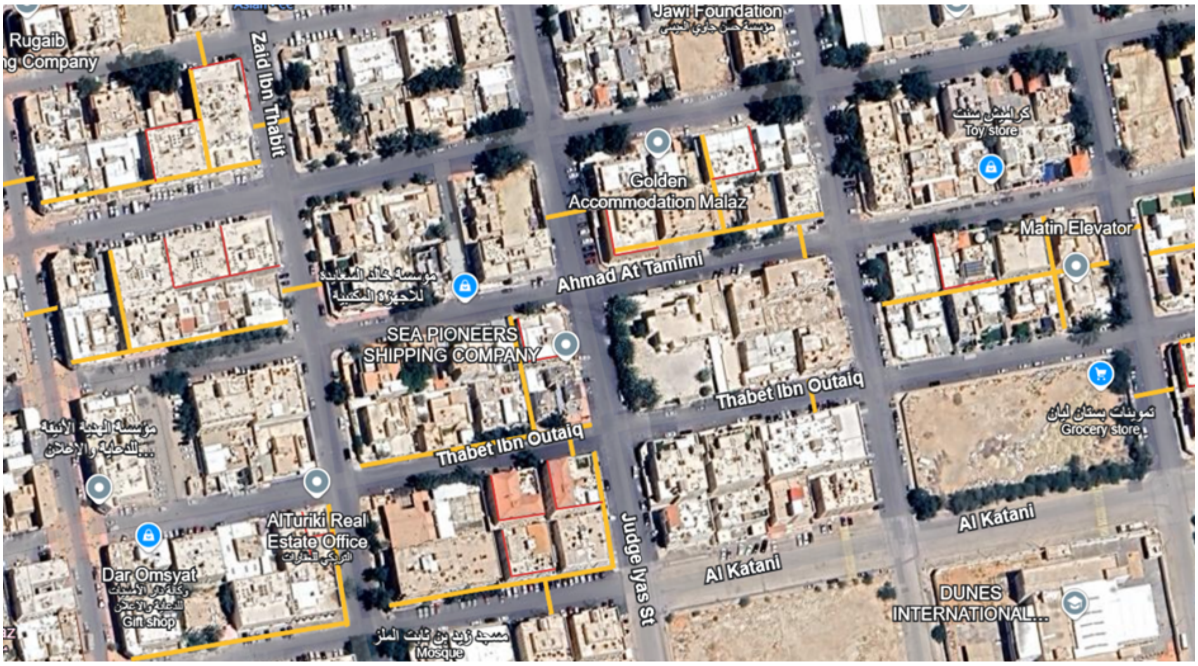
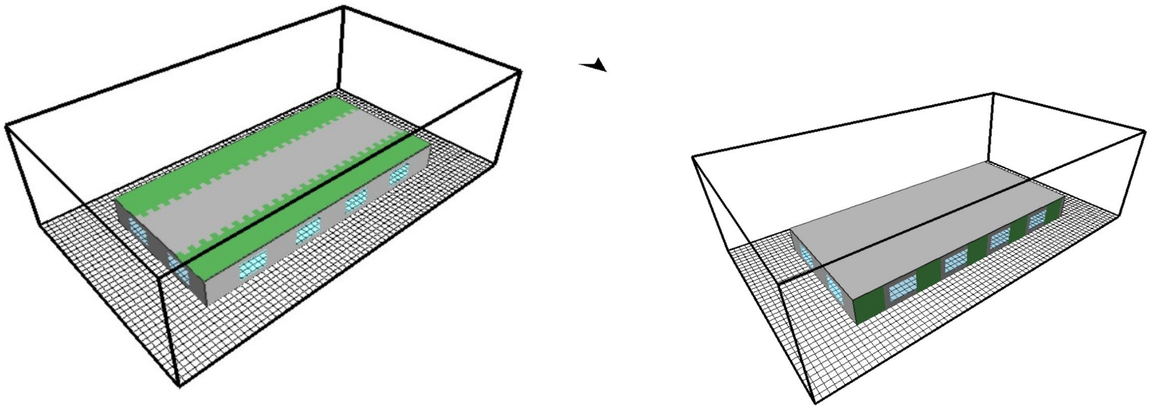


Figure 3.2: Fragment of the measurements gathered from the Al Malaz district. *Google Earth*.

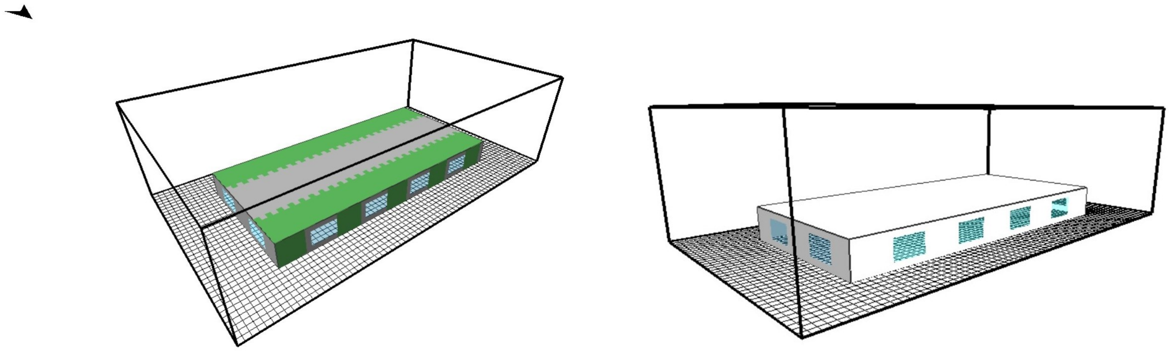
The model itself consists of a single housing block, bordered by streets on all sides, resulting in a grid-like structure with four streets total (figure 3.2). Due to computing limitations, the model assumed that the housing block was a singular structure, rather than a conglomerate of 8 buildings. The materials for the model were based on typical construction in Riyadh: houses are made of concrete, and roads are composed of asphalt. For the model, the construction of the wall assumes 3 layers. From outdoor to indoor, these are: a thin layer of plaster, a thin layer of insulation and a layer of concrete, preset in ENVI-met as default concrete. Based on observation during the field research as well as subsequent desk research, window size and shape seem to vary per construction, but the Saudi Building Codes dictate that windows-to-walls ratio (WWR) should not exceed 50% for commercial buildings (Asfour, 2020). To determine the energy performance of a standalone residential villa in Riyadh, Alaidroos & Krarti (2015) established a base-case of a typical detached villa built in Dharan with masonry material, with a WWR of 13%. Despite the authors noting that it is particularly low, for this model each wall facing sidewalk will have a ratio of 13% windows. Each wall is 225 m², hence 29.25 m² would be glazing. This is rounded down to 30 m² in the model. In the above-mentioned study, the villa was standalone, meaning it had no adjacent wall with another building. The authors did note that the 13% ratio was low. For this model, each wall facing sidewalk will have a ratio of 13% windows. This does mean that a singular overall house will have less than a 13% WWR, but rather a ratio ranging from 7% to 10%

depending on if two or three walls were adjacent to a sidewalk. The reason this was selected over the option to have the percentages of windows totalling to 13% over the entire house is because the field research conducted beforehand revealed that residential construction had relatively small and few windows. As such, the walls that were exposed would have a WWR up to 27%, which appeared to be unrealistic. After creating the digital model of Al Malaz, a series of baseline simulations were performed using ENVI-met to establish the existing Urban Heat Island (UHI) effects without the addition of any green infrastructure. This provided a foundational understanding of the current micro-climatic conditions in the district.

Following the baseline simulation, multiple scenarios were tested by varying the type of urban green infrastructure (UGI). The first scenario is one with 50% GR (figure 3.3a), another one consists of 50% GW on the wall facing north (figure 3.3b), and finally one consists of both 50% GR and 50% GW on the wall facing north (figure 3.3c). The vegetation used in all simulations was selected from the pre-set options within ENVI-met. As a comparison, simulations with white walls were also conducted (figure 3.3d). These simulations using white walls, which have reflective properties, are set in ENVI-met, to evaluate their cooling effect compared to green infrastructure. White walls are not an option in ENVI-met, but can be mimicked by adjusting certain parameter values of the walls using the DBManager. To mimic a white coat, the absorption of the default concrete was set to 0.66 (El-Gayar et al., 2014), reflectance was set to 0.85 (Li et al., 2021) and emissivity was set to 0.85 (Rosso et al., 2017). The other parameters remain unchanged. The windows selected for this model were one-layered (0200G4). From these four scenarios, 22 analytical graphs were obtained. One for each scenario at measured at a height of 140cm (five in total), followed by another five graphs measuring the results at 180cm. 12 comparative graphs were obtained, using the ENVI-met compare tool in Leonardo tool. A comparative simulation of each scenario against the base (no modification) was run at 8am, 3pm and finally 10pm.



(a) 3D rendering of the model created for the Green Roof Scenario. **(b)** 3D rendering of the model created for the Green Wall Scenario.



(c) 3D rendering of the model created for the combined Green Roof and Green Wall Scenario.

(d) 3D rendering of the model created for the Reflective Coat Scenario.

Figure 3.3: 3D rendering of various modelling scenarios. *ENVI-met.*

An overview of all the scenarios can be visualized in the table below (table 3.1).

SCENARIO	RUN TYPE	Height	Time
BASELINE	SINGLE RUN	140cm	3pm
	SINGLE RUN	180cm	3pm
GR	SINGLE RUN	140cm	3pm
	SINGLE RUN	180cm	3pm
	COMPARATIVE RUN	140cm	8am
	COMPARATIVE RUN	140cm	3pm
	COMPARATIVE RUN	140cm	10pm
GW	SINGLE RUN	140cm	3pm
	SINGLE RUN	180cm	3pm
	COMPARATIVE RUN	140cm	8am
	COMPARATIVE RUN	140cm	3pm
	COMPARATIVE RUN	140cm	10pm
COMBO	SINGLE RUN	140cm	3pm
	SINGLE RUN	180cm	3pm
	COMPARATIVE RUN	140cm	8am
	COMPARATIVE RUN	140cm	3pm
	COMPARATIVE RUN	140cm	10pm
WHITE	SINGLE RUN	140cm	3pm
	SINGLE RUN	180cm	3pm
	COMPARATIVE RUN	140cm	8am
	COMPARATIVE RUN	140cm	3pm
	COMPARATIVE RUN	140cm	10pm

Table 3.1: Comparative analysis of scenarios with varying heights and times. GR: Green Roof; GW: Green Wall; COMBO: Combined green roofs and green walls; WHITE: Reflective white paint. A single run shows the temperature gradient of the model without comparing different scenarios. A comparative run overlays a single run scenario with the baseline to visualize temperature differences.

The meteorological conditions for this study were carefully selected to represent typical extreme weather in Riyadh during the peak summer period, specifically on August 2, 2023. This date was chosen as it represents one of the hottest days of the month, providing an ideal scenario for assessing the impact of green infrastructure on mitigating urban heat.

The measurements were taken at King Khalid International Airport (Coordinates: 24°57′28″N 046°41′56″E / 24.95778°N 46.69889°E). A simple forcing model was applied, incorporating diurnal cycles of air temperature and specific humidity, with other parameters held constant. For precision, hourly data relative to humidity and air temperature on August 2023 were manually adjusted in the model (figure 3.2). Meteorological data was gathered either from Weather Underground, or from AQICN, both specific to the selected date. Parameters whose data could not be found, too uncertain or varying too much were left unchanged in ENVI-met, meaning that the simulation used the default values pre-set in the model for these specific values. Satellite images previously analysed indicated that no cloud coverage was present, as such the values for low, medium and high clouds were set to 0.

The simulation was run using the ENVI-met simple forcing method. An overview of the simulation parameters can be found below:

- Location: Al Malaz, Riyadh, Saudi Arabia
- Simulation Date: August 2, 2023

Time	T (°C)	rH (%)
00:00	33.89	9.00
01:00	32.78	8.00
02:00	32.78	9.00
03:00	32.22	9.00
04:00	30.00	12.00
05:00	30.00	13.00
06:00	28.89	11.00
07:00	32.22	10.00
08:00	35.00	7.00
09:00	40.00	6.00
10:00	42.22	5.00
11:00	43.89	5.00
12:00	45.00	4.00
13:00	46.11	4.00
14:00	46.11	4.00
15:00	46.11	4.00
16:00	46.11	4.00
17:00	43.89	5.00
18:00	43.89	5.00
19:00	41.11	5.00
20:00	41.11	5.00
21:00	40.00	5.00
22:00	37.78	6.00
23:00	37.22	6.00

Table 3.2: Air Temperature (T) and Relative Humidity (rH) by Time

- Start Time: 00:00 (Midnight)
- End Time: 23:00
- Total Simulation Time: 24 hours
- Max Air Temperature: 46◦C at 1:00 PM
- Min Air Temperature: 29◦C at 6:00 AM
- Humidity:
  - Min Relative Humidity: 4% at 1:00 PM
  - Max Relative Humidity: 13% at 5:00 AM
- Wind Speed: 2 mph. Corresponds to minimal wind speed on said date
- Wind Direction: 90° (standard, untouched)
- Roughness Length of surface: 0.010m (standard, untouched))
- Cloud Cover (range 0-8):
  - Low Clouds: 0
  - Medium Clouds: 0
  - High Clouds: 0
- Air Quality Index (AQI): 33 (indicating "Good" air quality)

The simulation begins at midnight and runs for 24 hours. The highest air temperature of 46°C occurs at 1:00 PM, with a significant temperature gradient observed between day and night. The lowest temperature of 29°C is recorded at 6:00 AM. Relative humidity peaks at 13% in the early morning around 5:00 AM and drops to a minimum of 4% in the early afternoon, coinciding with the highest temperatures and wind speeds. Wind conditions were also varied, with speeds ranging from 2 mph at their lowest, to 6 mph at 1:00 PM, blowing predominantly from the north to north-northeast. These conditions offer a clear representation of the typical hot, dry, and cloudless climate of Riyadh during the summer months, making it an ideal setting for assessing the impact of green roofs and walls on urban microclimates in extreme heat. These parameters, sourced from Weather Underground and WeatherSpark, provide a realistic baseline for simulating how green infrastructure might influence temperature regulation, air quality, and overall urban resilience under Riyadh's harsh summer conditions.

4

Results

4.1. Field Work

From the observations made during fieldwork, the architecture and urban landscape of Riyadh can be generally categorized into three distinct styles: Najdi/Vernacular, Concrete Block (including residential areas), and Neo-futurism. Each of these forms represents different periods and priorities in Riyadh's urban development. The prevalence of each of these structures was observed to inform the microclimate model. The Najdi or Vernacular style is reflective of traditional Saudi architecture, characterized by the use of adobe and mud-brick materials, which provide natural insulation from extreme heat. This style, although less common in new constructions, appears to be experiencing a resurgence, as there seems to be a growing interest in returning to traditional forms. This trend reflects a desire to reconnect with the cultural heritage, likely driven by ongoing conservation efforts. The Concrete Block style is prevalent in older commercial and residential areas and represents a more utilitarian approach to architecture. This style emerged during Riyadh's rapid urban expansion in the latter half of the 20th century, aiming for efficiency and scalability. These neighbourhoods are typically dense, lacking in green spaces, and predominantly constructed around cars as the primary mode of transportation. The dominance of impermeable surfaces in these areas also contributes to water stagnation when it rains, as the city lacks sufficient stormwater management infrastructure. This can lead to localized flooding. The Neo-futurism style, which can be seen in newer developments, is marked by modern architectural forms, glass facades, and innovative materials. This style often includes elements of green urbanism, albeit mostly for aesthetic purposes rather than functional green infrastructure. Examples of urban reforestation, such as green roofs and walls, are present along key roads like King Fahd Road and on prominent buildings, such as the MUMRA (Ministry of Municipal, Rural Affairs, and Housing) and FAFD (Future Architecture Forum Development). However, while these elements add to the appeal of the city, their impact on cooling and air quality appears to be minimal. In terms of urban structure, Riyadh is car-centric, with sprawling networks of wide roads and intersections that prioritize vehicle traffic over pedestrian accessibility. The city's layout shows a stark lack of third places: social spaces such as parks, plazas, and public gardens where people can gather. The many shopping malls seem to be the exception, serving as informal third places that attract residents from across the city. The city's desert environment adds another layer of complexity to urban planning. Riyadh is situated on a landscape surrounded by red sand and valleys.

Figure 4.1: Image of an overflowing drainage gullie.

4.2. Interviews

Expert interviews were coded and divided between Open Coding and Axial Coding (Appendix C, Figure C.2). The aim of these interviews was to help guide and conceptualize the microclimate model which follow suit. The expert interviews revealed several critical insights into the feasibility and challenges of implementing green roofs and walls in Riyadh, emphasizing the unique environmental and structural considerations of this arid urban landscape. One prominent issue identified was the significant weight load associated with green roofs. Riyadh's harsh environmental conditions bring hard limitations on green building initiatives. Extensive green roofs, which are often designed with shallow soil layers to minimize weight, were described as unsuitable for Riyadh's extreme climate. Experts noted that such shallow soils “fail to buffer” against the intense solar radiation, which leads to overheating. In Riyadh's climate, soil depths of at least 50 cm, typically reserved from intensive green roofs, would be required to retain sufficient moisture and protect plant roots from the harsh sun, However, this would be adding considerable weight that many existing buildings may not be equipped to support.

Another major finding relates to plant selection and adaptation to the local climate. Given Riyadh's extreme temperatures, with lower temperatures siting at around 15°C in the winter but exceeding 50°C in the summer, vegetation must be highly resilient, particularly in light of occasional heavy rainfall. Experts emphasized the importance of drought-resistant plants that can survive both extreme heat and occasional cold spells. Local or adapted species like lavender, mint, and oregano were highlighted as viable options, as these plants are both drought-tolerant and suited to the region's unique conditions. However, a critical drawback of drought-resistant plants is their tendency to absorb atmospheric humidity, which can inadvertently contribute to a drier atmosphere, which would pose as a big concern in Riyadh's already dry environment. To counteract this, experts suggested irrigating these plants frequently to encourage evapotranspiration and help cool the surrounding air. This, however, increases water demand, raising questions about sustainability given Riyadh's limited water resources.

Retrofitting older buildings to accommodate green roofs and walls also presents many challenges. According to some interviewees, many existing structures may lack the necessary documentation to assess their load-bearing capacity, requiring new structural assessments that can be both complex and costly. Experts emphasized the importance of involving urban planners early in the design process to navigate these challenges effectively and to ensure that any new green infrastructure aligns with Riyadh's existing urban landscape. Retrofitting, while feasible, is resource-intensive and adds an additional layer of difficulty to the implementation of green infrastructure in the city.

Moreover, experts raised questions about whether green roofs and walls offer a significant enough benefit over more straightforward alternatives, such as painting building surfaces with reflective white coatings such as those found in Greece or Italy. White paint, which reflects solar radiation and reduces heat absorption, could provide a comparable cooling effect without the need for extensive maintenance and irrigation. Under intense sunlight, reflective coatings are a cost-effective and low-maintenance option that can decrease heat perception without the complexities associated with green infrastructure. Thus, the experts suggested that green roofs and walls should only be considered if they provide a substantial advantage over these simpler solutions.

The interviews also highlighted specific design and urbanism considerations for green infrastructure in Riyadh. Green walls would have to face north as to be away from direct sunlight, as to avoid the plants overheating and dying as a result. When selecting plants, experts recommended using species that are not only drought-tolerant but also slow-growing to minimize the need for pruning and maintenance. Locally grown plants would be preferred, with preference for species that thrive under extreme conditions. However, local plant nurseries are already at capacity, and extra orders could be difficult to complete. Climbing plants and vines were suggested for green walls, as they can grow with limited soil and withstand varying light conditions. Additionally, walls were preferred over roofs as wall structure do not need to rest directly on the building, but instead can “hover” over it. Experts also emphasized the role of reflective surfaces, such as concrete, to complement green infrastructure by creating natural shade and reducing heat retention.

Stormwater management was another important consideration. Riyadh's propensity for flash floods underscores the need for sustainable drainage solutions. Green roofs can help by reducing stormwater runoff, though green walls contribute less directly to this aspect. Experts discussed the potential of bioretention systems, such as rain gardens, to capture and reuse rainwater for irrigation. However, the effectiveness of green infrastructure for stormwater management in Riyadh is limited by the lack of sufficient surface area on green walls for meaningful water retention.

While several insights were gained from the interviews, only specific themes were included in the model (figure 4.2). Information on load resistance and retrofitting as a result of these new installations were not taken into account in the model. Other information, such are vegetation and humidity were taken into account, but within limits. For instance, the model did not take into account how different vegetative species would impact the roofs or walls, while humidity was only taken into account in the form of meteorological data, but not analysed for thermal comfort.

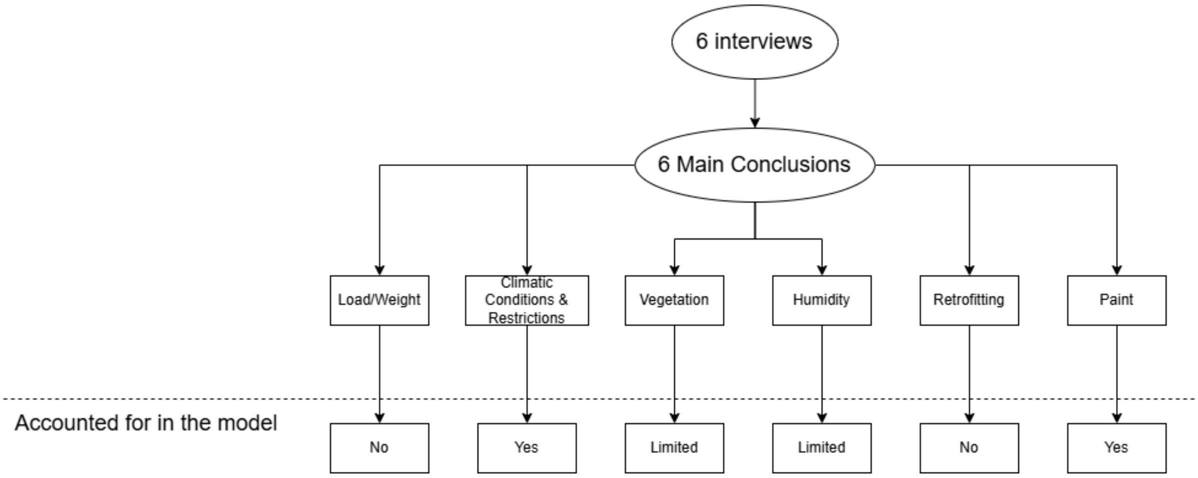


Figure 4.2: Schemnatic overview of the information accounted for in the final model

4.3. Remote Sensing

To complement the findings obtained from the fieldwork and the interviews, geospatial analysis is performed to gain a better understanding of the layout and urban ecosystem of Riyadh. Through remote sensing, cityscape thermal behaviour can be identified, as to visualize how natural processes can influence thermal efficiency in line with NBS best practices.

4.3.1. Initial image processing and Vegetation

GIS enhancement

Figure 4.3 showcases a map of metropolitan area of Riyadh. The original map, in greyscale, was obtained through Egis who processed and colour-corrected the map. While the NDVI cover was calculated separately shortly after to process the Land Surface Temperature and obtain precise measurement values, the vegetation data displayed here originates from a shapefile containing vegetation information for the wider metropolitan area of Riyadh, also provided by Egis. This enabled the vegetation cover to be easily overlaid onto a greyscale map without including unnecessary information.

Urban Fabric and Layout

The central area shows a dense urban grid, indicative of Riyadh's city centre. Streets, buildings, and infrastructure create a clear network of organized patterns, typical of an urban environment. Major roads and highways appear as bold linear features connecting various parts of the city. The highway network is very distinctively noticeable, spreading out from the central zones toward the outskirts. An urban sprawl from the inner city towards the desert is evident, with developments that appear to extend in all directions, but especially toward the northeast and southwest.

Vegetation

Figure 4.3 reveals a diverse distribution of natural and man-planted vegetation in Riyadh, which plays a significant role in moderating the city's harsh desert climate. The vegetation, highlighted in green,

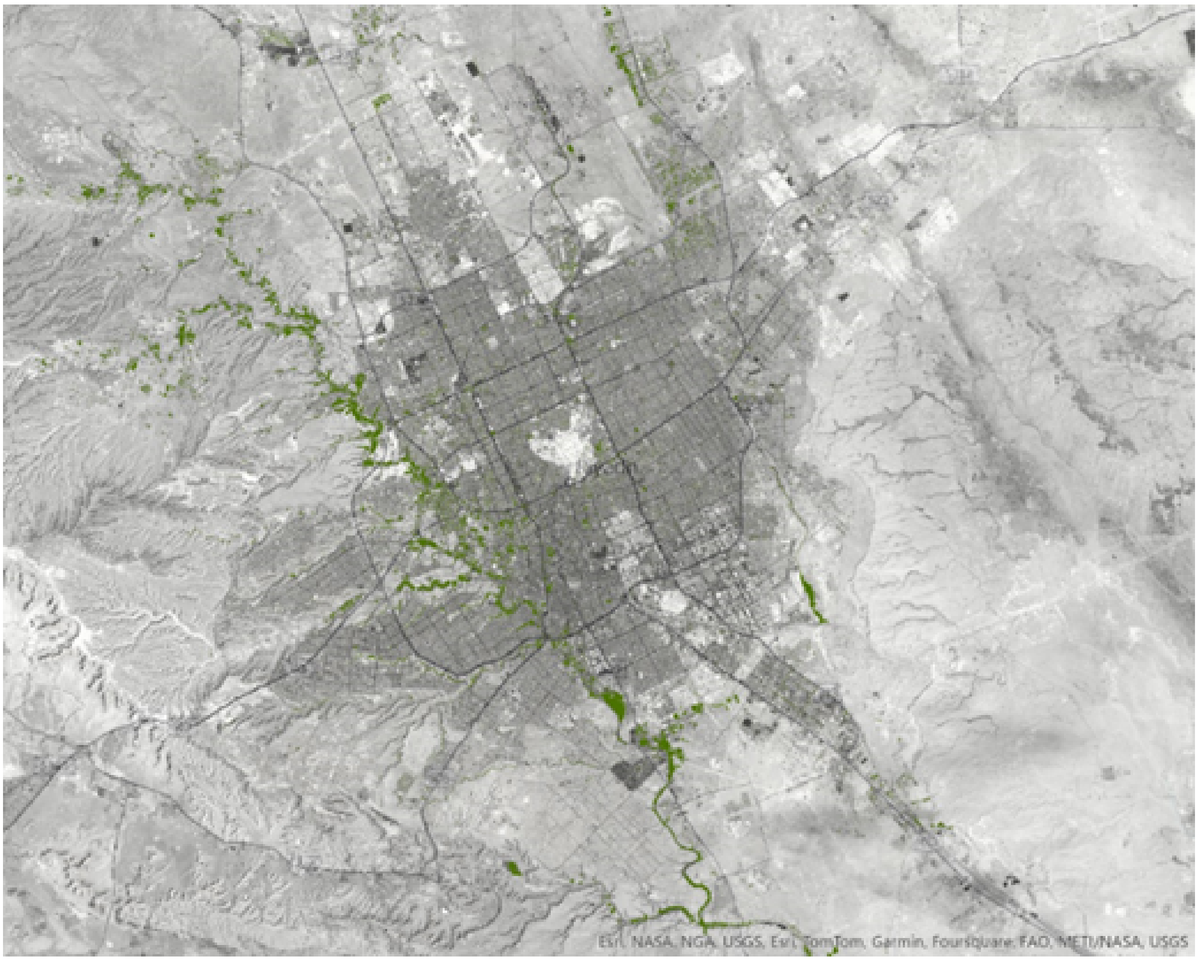


Figure 4.3: Satellite imaging of the vegetation cover superimposed over the city of Riyadh, Saudi Arabia. *ArcGIS*.

appears sparse but is instead located throughout key parts of the city. Most of the vegetation is concentrated along wadis (river valleys), or spaced out throughout the city. Natural vegetation is most prominently found along Wadi Hanifa, where it flourishes due to consistent water availability, to form a belt. This would have originally been the delimiter of the city in the western direction. This stands in contrast to Wadi Al-Batha, where the vegetation appears to have dried up, due to the impact of urban development. Indeed, the vegetation in the eastern outskirts of the city seems minimal compared to the concentration westside, and near the urban core. Within the inner city, the vegetation is largely man-planted, distributed across parks and road medians, as well as (residential) landscaped areas. There are notable clusters of greenery visible in the image, in what seem to be major parks or cultivated areas. These greening efforts are guided by strict regulations as set out in the Manual of Ariyadh Plants, developed by the Royal Commission for Riyadh City. This manual ensures that the selected plant species are well-adapted to the arid conditions of Riyadh while fitting the aesthetic guidelines.

Topography

The surrounding desert terrain is a defining feature. In this image, the desert can be observed to the west and southeast of the city. These areas are visible in a lighter grey, indicating less density and less infrastructure. However, contrasting shades of grey are visible throughout the desert. It appears rugged, with visible escarpments and elevated areas. These are likely natural rock formations, such as mesas or valleys. In contrast, the city appears flat in most areas: while the area is typically a darker shade of grey, there appears to be no outline of an elevated area. This indicates a low-lying plateau, which would make sense for early settlements and city developments. This visualization underscores Riyadh's arid environment, where vegetation is scarce and predominantly dependent on irrigation or specific natural features (e.g., wadis or parks).

4.3.2. Land Surface Temperature

The resulting image was obtained using LANDSAT 8 images, processed using the Mono-Window Algorithm as detailed in chapter 3.3. The remote sensing analysis for August 18th and 25th, 2023, shows a marked temperature gradient across Riyadh and the surrounding desert areas at 7 AM on both days (figure 4.4). The city of Riyadh is located at the centre of the image. Although the east and west images were taken a week apart, they provide valuable insights into the city's temperature distribution. The temperature range spans from approx. 27°C (dark blue) in cooler areas to approx. 60°C (dark red) in the hottest zones. Riyadh city is generally cooler than the outer desert, with cool pockets appearing in blue, particularly around valleys where topography and vegetation naturally contribute to cooling. Rather than an UHI, one could refer to an 'Urban Cooling Island'.

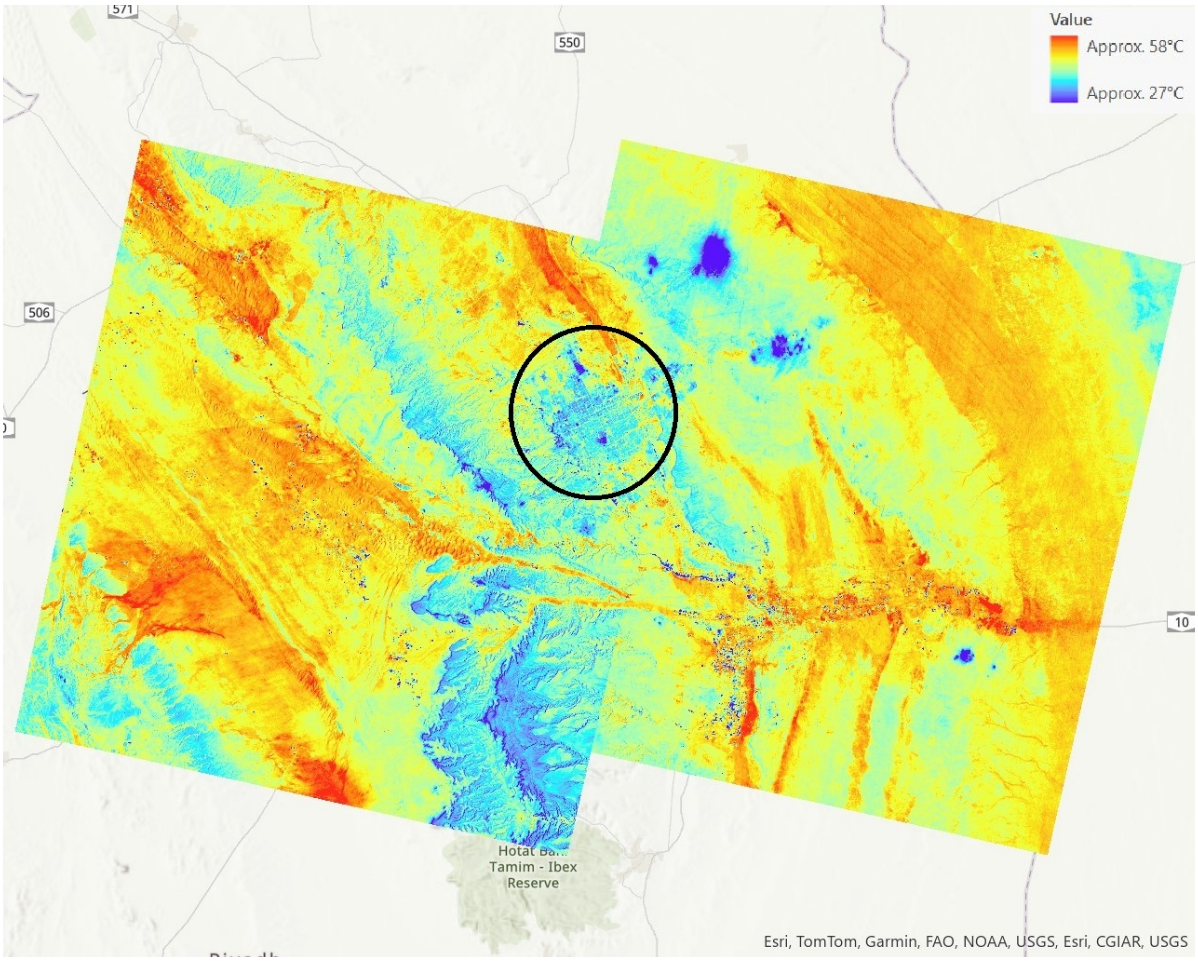


Figure 4.4: Processed satellite imaging of the land surface temperature across Riyadh (circled in black) and neighbouring open desert. The scale ranges from approx. 27°C (dark blue) to approx. 60°C (dark red). *ArcGIS*.

Temperature Distribution and Patterns

Temperature distribution and patterns were assessed by overlaying various shapefiles onto the LST map, including vegetation, land use (figure 4.5), and natural elevation and valleys (figure 4.7), provided by Egis.

Hot Areas

Most of the area is dominated by red and orange hues, indicating higher surface temperatures relative to the rest of the area. Here, temperature ranges from approx. 50°C (orange hues) to approx. 60°C (red hues), typical of an arid, desert climate. The higher temperature zones are widespread in flat, open desert areas, where there is little vegetation or water to moderate surface heat. These regions likely experience intense solar heating, consistent with the climate of the Arabian Peninsula in open land.

Within the wider region of Riyadh, such temperature profiles are found mostly on the outer eastern and western edges of the studies area, outside the boundary of the city of Riyadh.

Patches of blue and cyan represent cooler areas, which are likely associated with vegetation, or areas shaded by topography such as valleys and wadis. Temperatures of such areas range from approx. 27°C (blue) to approx. 45°C (cyan). Noticeable cooler zones may correspond to wadis, where natural depressions retain moisture or support vegetation, vegetated lands, reflecting either agricultural activity or landscaping, or elevated terrains, such as valleys.

Cooler Areas

Elevated terrains promote cooling by provide shade to its surroundings, resulting in temperatures which are typically lower compared to land which does not have neighbouring altitudes. Within the wider region of Riyadh, such temperature profiles are mostly found within the edge of the city, but can also be noticed outside the boundary of the city, near and around areas which appear to be elevated and would correspond to valleys (figure 4.5).

Contrast in temperatures

The temperature gradient suggests hotspots in areas without vegetation cover, shade or moisture and cooler zones in areas with vegetation, shade or water (figure 4.6a). There appears to be a stark thermal contrast between the urbanized zones, where heat is reduced due to tall buildings which provide shade (figure 4.6b), and the surrounding rural and desert areas, which remain largely exposed (figure 4.4). Likewise, a contrast can be noted between open desert, and desert areas with elevation which can provide shade. The latter shows significant temperature reduction, with measured temperatures most similar to those within the inner city of Riyadh. The elevated areas appear to be extensive in both length and width, creating several gigametres of cooling within the desert. This does seem to imply that people are generally better off living in an urbanized environment rather than the open desert.

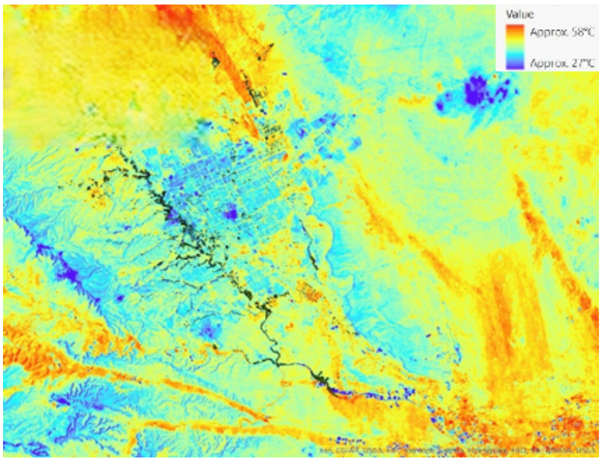
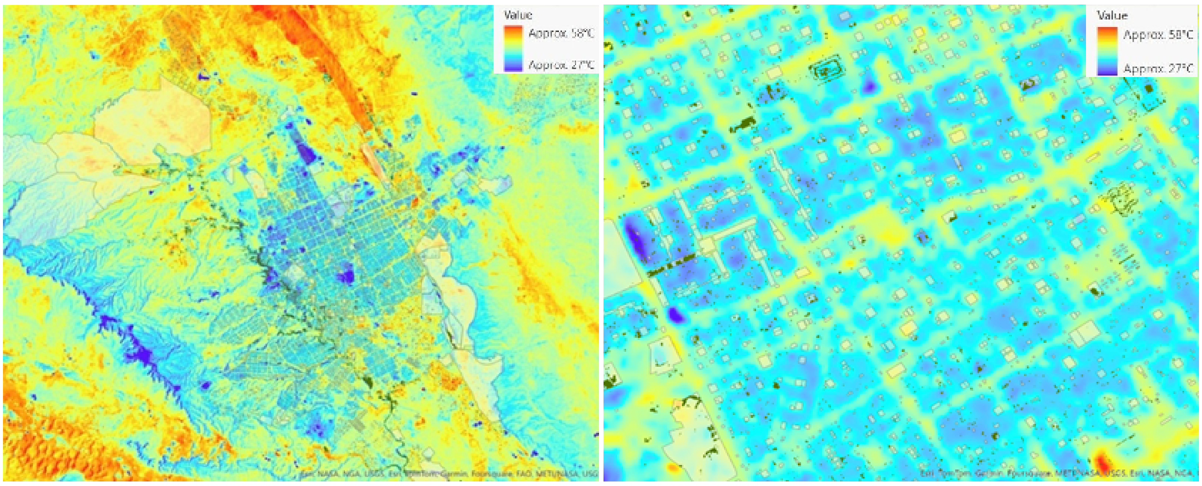


Figure 4.5: Magnified satellite imaging of the land surface temperature across Riyadh, with superimposed vegetation cover. The scale ranges from approx. 27°C (dark blue) to approx. 60°C (dark red). *ArcGIS*.



(a) Land surface temperature with overlaid land use (outline) and vegetation cover (in green). The scale ranges from approx. 27°C (dark blue) to approx. 60°C (dark red).

(b) Magnified land surface temperature with overlaid land use (outlines) and vegetation cover (in green). The scale ranges from approx. 27°C (dark blue) to approx. 60°C (dark red).

Figure 4.6: Satellite images of the Land Surface Temperature overlaid with land use and vegetation data. *ArcGIS*.

4.3.3. Land Use & Natural elevation

An overlay with land-use data highlights how densely built-up inner-city areas create shading, which reduces heat absorption and provides cooler micro-climates (figures 4.6a, 4.6b). These shaded areas demonstrate that urban structures in Riyadh can mitigate heat, especially during peak summer months, by limiting direct solar exposure. Figure 4.5 further supports these findings, showing that temperatures are significantly lower near vegetated areas within the city. These pockets of greenery help alleviate the urban heat island effect by reducing surface temperatures and fostering localized cooling. Furthermore, significantly lower temperatures are recorded near and around areas with natural elevations, such as valleys (figure 4.7). Figure 4.7 also highlights Riyadh's unique positioning, located between valleys and around cracks in the plateaux, and underscores the difficulties in expanding further into the desert. Conversely, the hottest areas within the studied zones are located in the middle of the desert, where there is no shading from valleys, and where vegetation and artificial shading from buildings are absent (figure 4.5). These desert zones, far removed from the cooling effects of the city centre, remain exposed to direct solar radiation, leading to extreme heat retention. However, it is important to note that while the inner city is generally cooler, the recorded temperature at 7am is still 29 degrees, while the ideal temperature for the human body falls between 20 to 25 degrees Celsius (University of Arizona, 2012).

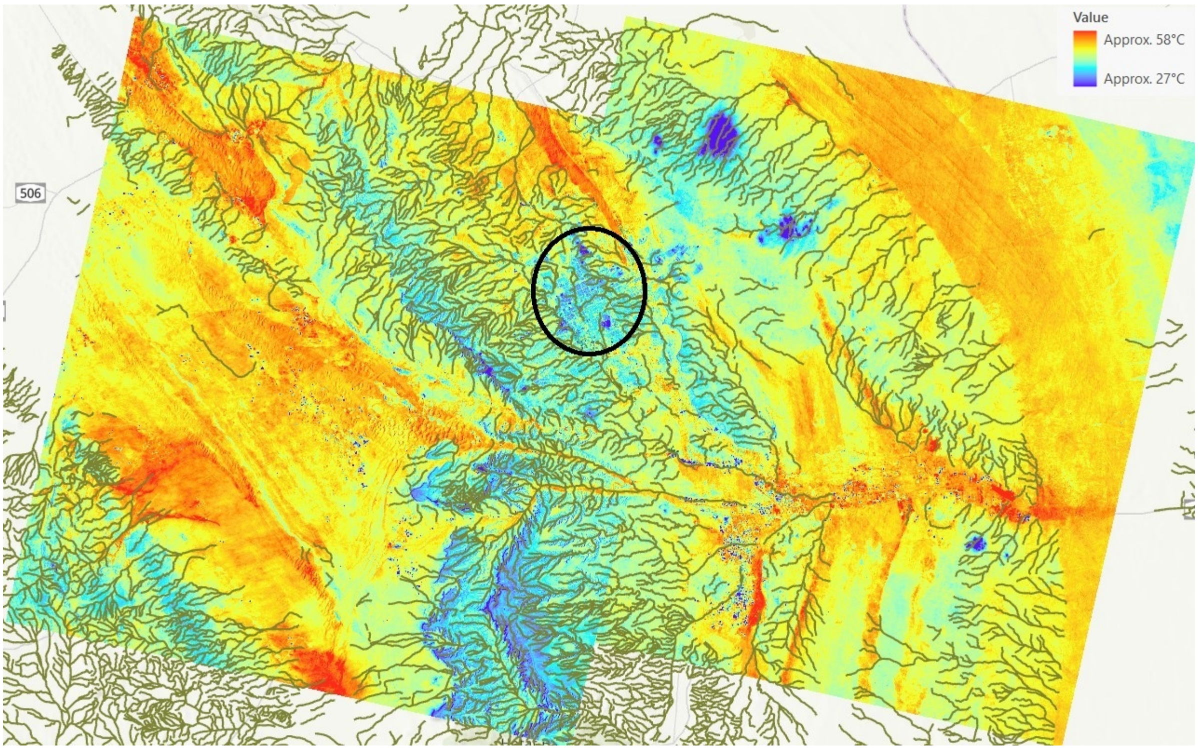


Figure 4.7: Processed satellite imaging of the land surface temperature across Riyadh (circled in black) and neighbouring open desert, overlaid with natural elevation. The scale ranges from approx. 27°C (dark blue) to approx. 60°C (dark red). *ArcGIS*.

A temperature gradient across the wider region of Riyadh is derived using the shapefile processed by Egis and LANDSAT 8 images processed using the mono-window algorithm. Temperature range from 27°C to 58°C. Areas in blue, which are associated with lower temperatures, are mostly found in the centre of the imaged area and toward the south and the north-east. Overlaying these area with the shapefiles obtained by Egis gives a comprehensive view of how variation in the terrain affect LST. Areas with shade as a result of nearby buildings and nearby vegetation consistently record significantly lower temperatures. Riyadh, rather than being a typical ”Urban Heat Island,” can be seen as an ”Urban Cool Island” due to the abundance of shading provided by its buildings, which offer protection from the desert sun. This highlights that living in the city is far preferable to the open desert, where temperatures can soar up to 30°C higher. However, the relative ”coolness” is limited. Temperatures in most parts of the city exceed 27°C by 7 am, far above the optimal thermal comfort levels suggested in the literature. The findings underscore the need for continued efforts to enhance thermal comfort. Instead of focusing on citywide cooling, the findings suggest that localized interventions can deliver significant benefits. Cooling efforts should prioritize microclimate solutions, such as green walls, green roofs, or reflective coatings, which align with NBS and emerged as promising strategies in the interviews.

4.4. Micro-Climate Modelling

The micro-climate model is built to be an archetype of a building in Riyadh, informed by the findings from the field work, interviews and remote sensing. The meteorological data used were retrieved for August 2nd 2023, as this corresponds to one of the hottest days of the year 2023. The temperature in Riyadh, taken at King Khalid International Airport, ranged between 29 and 46°C, while the relative humidity ranged from 4% to 13%. For comparison, the temperature in Delft (TU- Noord) over the same period ranged from 16 to 21°C, while the relative humidity ranged from 60% to 94%, with no precipitation recorded that day. The measures for Barcelona, taken at Josep Tarradellas Barcelona-El Prat Airport Station ranged from 24 to 30°C, and the relative humidity from 70% to 89% with no precipitation recorded that day. At Milan Linate Airport Station, temperature varied between 20 and 30°C, and relative humidity between 51% and 88%, with no precipitation recorded that day.

4.4.1. Air temperature measurements for different scenario at different heights

The analysis of perceived temperatures around a building reveals how different design interventions can impact temperature variations throughout the day. The impact of the different scenario on the microclimate around the building can be measured at different heights. Here, the results are investigated at z=1.40m (k=3) and z=1.80m (k=4), as these heights give the best impression of what a person walking by would experience. For these first couple of simulations, all four scenarios (GR, GW, GR/GW and White wall) are measured at 1.40m and again at 1.80m, to be compared against the base scenario. The time selection for this forecast is 3pm local time, representing the hottest period of the day. In total, ten distinctive visualisations can be observed. Each visualization is printed out in 2D, pictured from above (helicopter view). Each rendering of the model is 140 metres long (west to east) and 80 meters wide (south to north). The x and the y axes represent the scale of the model, with the building being placed at the centre. The building is featured as a black rectangle ranging from 20 meters to 120 meters in the X direction and 15 meters to 65 meters in the Y direction. Surrounding the building, is a temperature gradient, which represent the variation in temperature of neighbouring street. This dispersion ranges from blue to red, with blue being the coldest measured temperature and red being the hottest measured temperature.

Base case

The base case (no roofs, no walls, no coating) shows significant temperature differences across the building surface at 140 centimetres above ground (z = 1.40m) (figure 4.8). Air temperature in this scenario reaches a high of 50.3°C near the south-facing wall and in the north-western direction but falls to 46.83°C east of the building. The south-facing wall shows the least variation in temperature across its projection, maintaining a temperature at around 49.61–49.95°C. The north-facing wall appears to vary more, with temperatures, ranging from 47.52°C to 49.95°C. The coolest temperatures are in the projection of the east-facing walls, where they hover between 46.83 and 48.91°C. Lower temperatures are also projected to be perceived adjacent to the west-facing wall, where they appear to be only marginally higher regarding its opposite wall (the west wall).

Slight variations can be noted when analysing the temperature differences across the building surface at 180 centimetres above ground (z = 1.80m) (figure 4.9). A slight decrease in temperature can be noticed at this height, as these measurements are taken further away from the pavement. The maximum air temperature measured is 50.04°C, while the lowest temperature recorded is 46.39°C. The temperature profile and distribution across the system remain similar to that observed at 140cm. Again, the south-facing wall shows the least variation in temperature across its projection, this time maintaining a slightly lower temperature at around 49-49.68°C. The north-facing continues to show great variation in the simulated temperatures, now ranging from 47.12°C to 49.68°C. Similar to the temperature profile at 140cm, the coolest temperatures can be found in the projection of the east-facing wall, 20 meters removed from the wall (x = 140m) at around 46.39°C. However, it fluctuates heavily in the interspace leading up to it. The hottest air temperatures (T > 49.68°C) are projected in the outmost corner of the north-facing wall (x = 0m, y = 80m), as well as extending across the south-facing wall. Interestingly, the air temperature adjacent to the west-facing wall appears to remain the same at both heights, sitting at around 47.15°C. This is particularly surprising, while the temperature profile is the same at both heights, the air temperature appears to be consistently a bit lower at 140cm than at 180cm everywhere else.

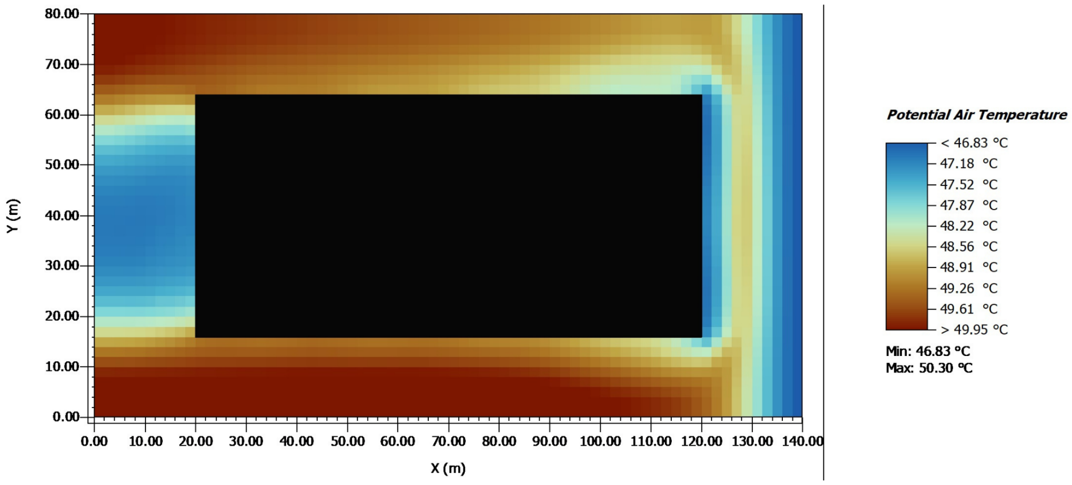


Figure 4.8: Microclimate results of Base case at 3pm, y = 140cm. *ENVI-met Leonardo*.

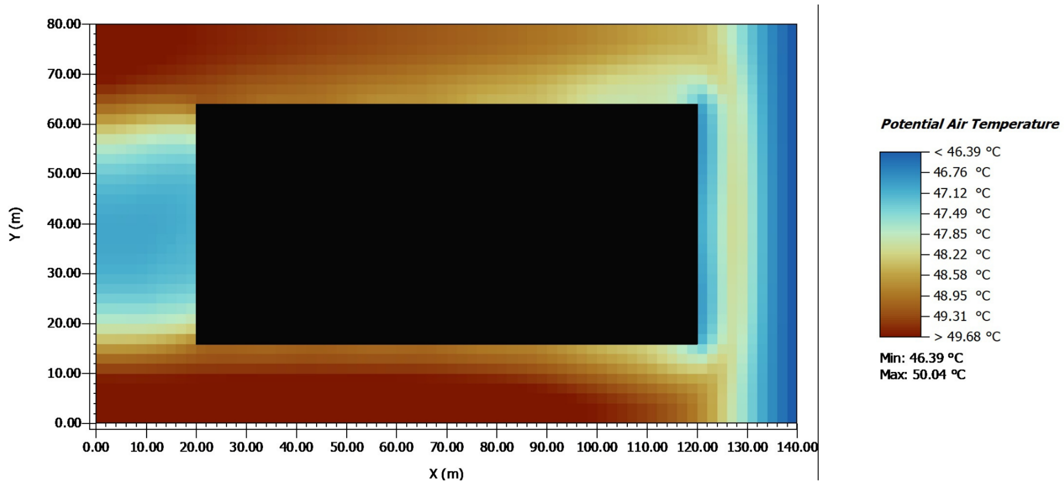


Figure 4.9: Microclimate results of Base case at 3pm, y = 180cm. *ENVI-met Leonardo*.

Green Roof Scenario

Adding green roofs to 50% of the baseline building's area yields a slight cooling effect, reducing the overall predicted maximum air temperature to 50.17°C at a height of 140cm (z = 1.40m), 3pm local time (figure 4.10). At this same height, the overall minimum predicted air temperature falls to 46.68°C. This cooling is most noticeable on the north-facing wall, where temperatures now range from 47.04°C to 49.47°C, representing an overall decrease of roughly 0.5°C compared to the baseline scenario. Additionally, a slight temperature reduction is projected in the direction of the west-facing wall, where the overall air temperature is now estimated to be sitting at around 46.69-47.04°C. The west-facing wall maintains a relatively constant air temperature, similar to the base scenario. Interestingly, the lowest temperatures are measured at the west-facing wall in this scenario, rather than at the east-facing wall in the baseline scenario, while remaining relatively constant in comparison. However, the projected air temperature at the east-facing wall remains low relative to the rest of the system. Temperatures of the east-facing wall fluctuate between 47.04 and 48.78°C, with the coolest temperature projected 20 meters away from the wall (x = 140m). The highest temperatures (T > 49.82°C) are measured at the south-facing wall, starting west (x = 0m) and expanding across the wall.

At 180cm above the ground (z = 1.80m), the projected air temperature shows some variation compared to the prediction at 140cm above ground (figure 4.11). While the temperature gradient remains widely the same, the profile varies slightly, ranging from 46.55 to 49.91°C. This corresponds to approximately a 0.25°C decrease in perceived air temperature compared to the projected temperature at 1.40 meters. The maximum temperatures are again measured west of the wall, in the street corners (x = 0m, y = 0m and y = 80m), while extending across the south-facing wall. The minimum temperatures are predicted to be adjacent to the west-facing wall, fluctuating at around 46.55-47.22°C, and in the projection of the east-facing wall (x= 130m to x=140m), fluctuating between 46.55-47.89°C. The highest temperatures (T > 49.57°C) are measured at the south-facing wall, starting west (x = 0m) and expanding across the wall.

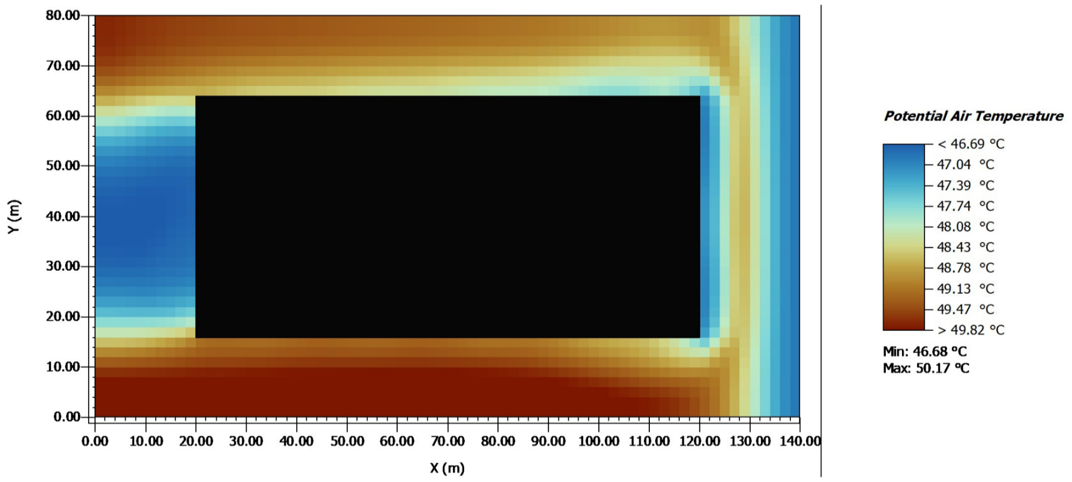


Figure 4.10: Microclimate results of Green Roof scenario at 3pm, y = 140cm. *ENVI-met Leonardo*.

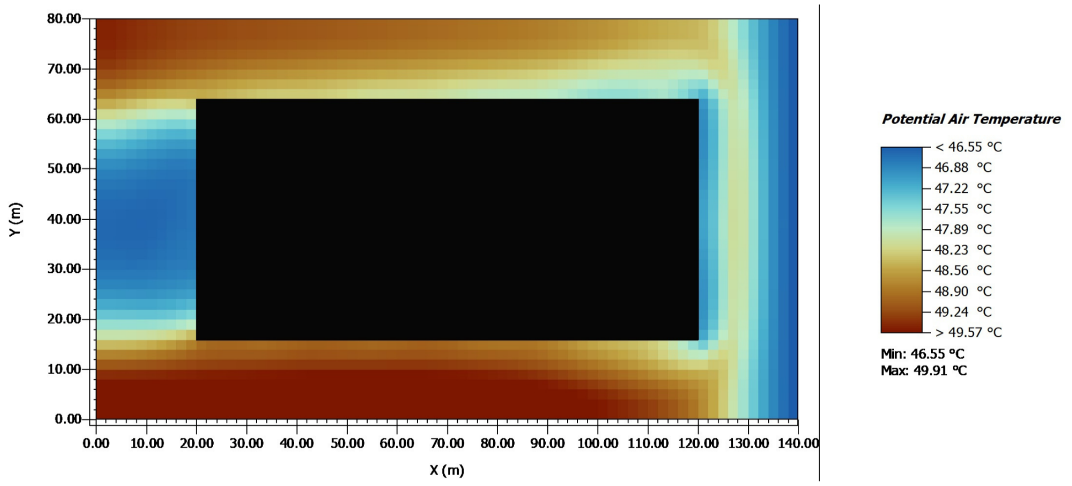


Figure 4.11: Microclimate results of Green Roof scenario at 3pm, y = 180cm. *ENVI-met Leonardo*.

Green Wall Scenario

When green walls are added specifically to 50% of the north-facing wall, the dispersion pattern of the air temperature shows only minimal cooling effects, similar to the green roof scenario alone (figure 4.12).

At a height of 140cm above ground (z = 1.40m), the temperature profile ranges from 46.96 to 50.18°C. At a height of 180cm above ground (z = 1.80m), the temperature profile ranges from 46.55 to 49.91°C, which is almost identical to the range projected with the green roof at the same height explored above. This seems to indicate that the cooling effect of a green wall, when they do occur, has less impact closer to the pavement despite the green wall in the model going all the way down (y = 0m).

At 1.40m above ground, the coldest temperatures are predicted to be in the street adjacent to the west-facing wall (x = 0 to 20m), sitting at 46.96-47.60°C, as well as in the outmost projection of the east-facing wall (x = 140m) (figure 4.13). The hottest temperatures, reaching up to 50.18°C, remains near and around the south-facing wall, and in the outmost left corner of the north-facing wall. At 180cm above ground, the coldest temperatures (T = 46.55 to 46.89°C) are predicted to be in the outmost projection of the east-facing wall (x = 140m). The air temperature of the west-facing wall (T = 47.22 to 47.56°C) is predicted to remain unchanged compared to the one estimated at 140m above ground.

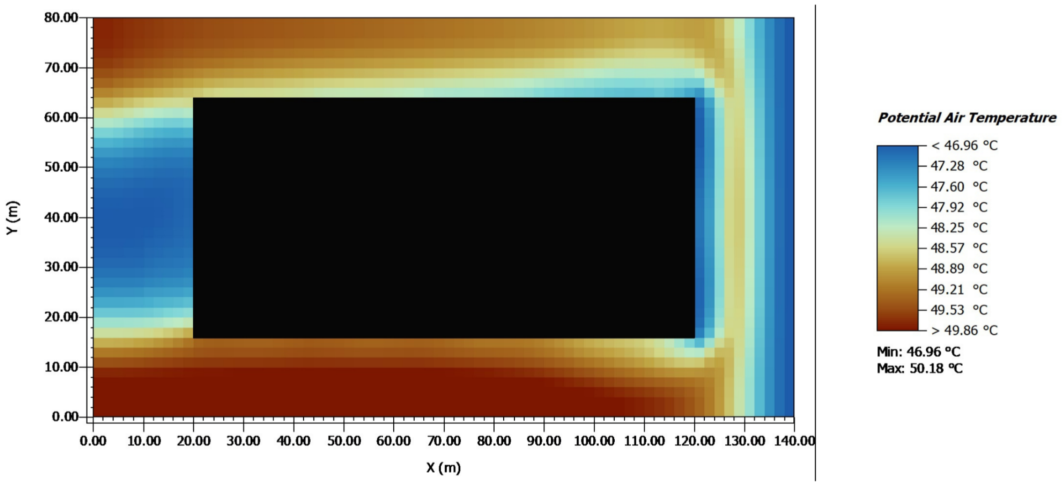


Figure 4.12: Microclimate results of Green Wall scenario at 3pm, y = 140cm. *ENVI-met Leonardo*.

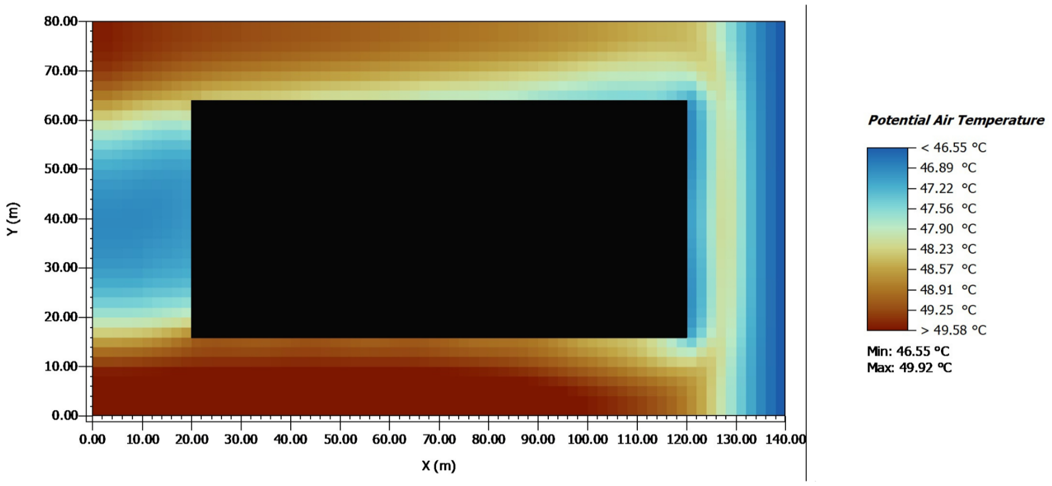


Figure 4.13: Microclimate results of Green Wall scenario at 3pm, y = 180cm. *ENVI-met Leonardo*.

Combination Scenario

When creating a scenario in which green roofs (at 50% coverage) and green walls (at 50% coverage on the north-facing wall) we continue to observe that the temperature dispersion remains largely unchanged (figure 4.14). At a height of 140cm (z = 1.40m) the predicted temperature ranges from 46.66

to 50.18°C. The lowest temperatures are expected to be in the direction of the east-facing wall (T = 46.66°C) at x = 140m, followed by the street adjacent to the west-facing wall, where the temperature ranges between 46.67 and 47.89°C. The hottest temperatures are predicted to be ranging from 49.12 to 50.18°C and are once more found facing the south-facing wall, as well as in the outmost left corner of the north-facing wall.

At 180cm above the ground (z = 1.80m), the predicted temperature is somewhat lower, ranging from 46.54 to 49.92°C (figure 4.15). The lowest temperatures are expected to be in the direction of the west-facing wall, maintaining a constant range between (T = 46.54 to 47.22°C), second by the eastern direction, which has more fluctuation. The temperature in the eastern direction ranges between 46.54 to 48.23°C. The hottest temperatures are predicted to be ranging from 48.90 to 49.92°C and are once more found facing the south-facing wall, as well as in the outmost left corner of the north-facing wall.

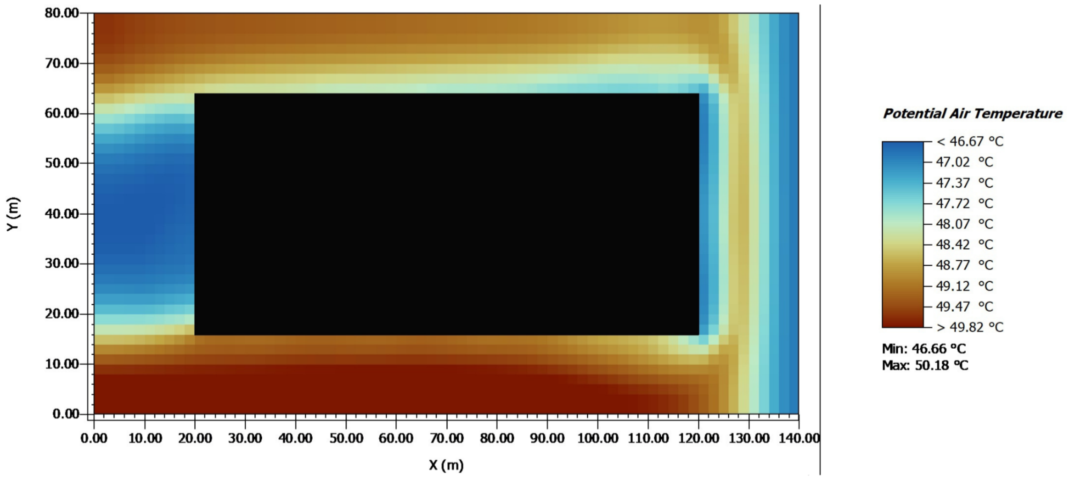


Figure 4.14: Microclimate results of Combined scenario at 3pm, y = 140cm. *ENVI-met Leonardo*.

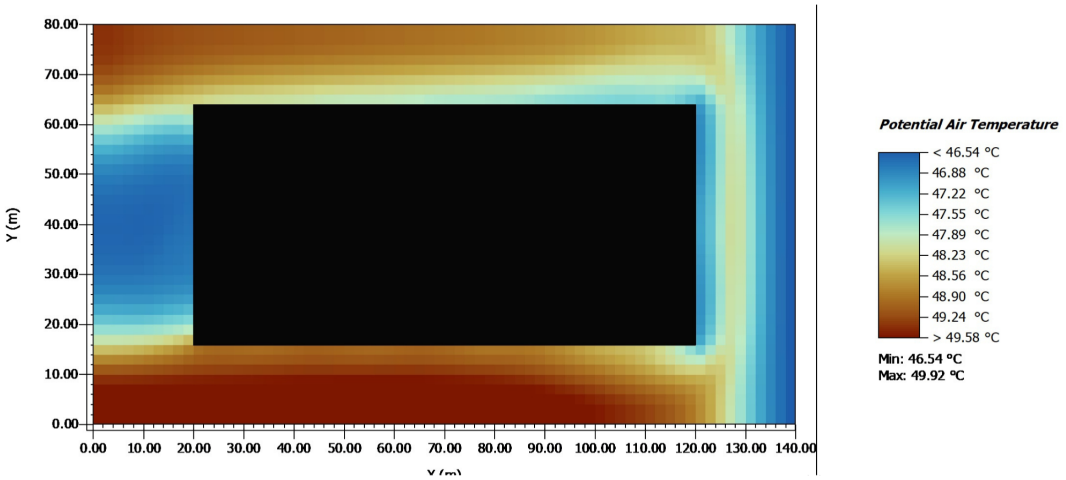


Figure 4.15: Microclimate results of Combined scenario at 3pm, y = 180cm. *ENVI-met Leonardo*.

Reflective Coat Scenario

A final scenario is examined, in which the entirity of the building is painted white. This scenario serves as an alternative option to vegetation. The predicted air temperature at a height of 140cm (z = 1.40m) the predicted temperature ranges from 46.96 to 50.19°C (figure 4.16). The lowest temperatures are measured in the direction of the east-facing wall (T = 46.96 to 48.57°C), followed by the west-facing wall

(T > 46.96 to 47.93°C). The hottest temperatures are predicted to be ranging from 49.22 to 50.19°C, and can be found in the across the south-facing wall, as well as in the outmost left corner of the north-facing wall. At 180cm above the ground (z = 1.80m), the predicted temperature drops to a range between 46.55 to 49.93°C (figure 4.17). The lowest temperature is expected to be in the projection of the east-facing wall (x = 140m), ranging from 46.55 to 47.23°C. Low temperatures are also found in the direction of the west-facing wall, with temperatures ranging between 46.89 to 47.90°C). The hottest temperatures are predicted to be ranging from 48.92 to 49.93°C and most noticeable facing the south-facing wall, as well as in the outmost left corner of the north-facing wall.

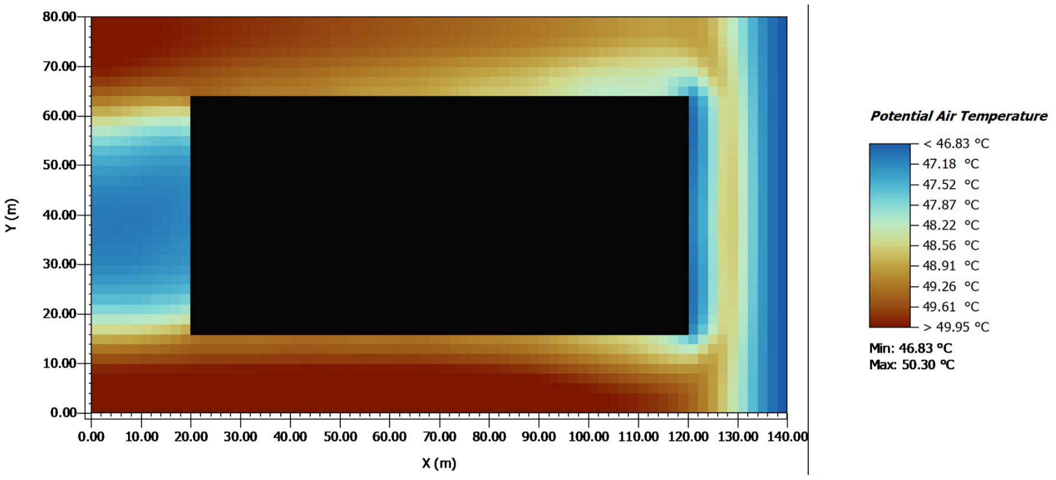


Figure 4.16: Microclimate results of White Paint scenario at 3pm, y = 140cm. *ENVI-met Leonardo*.

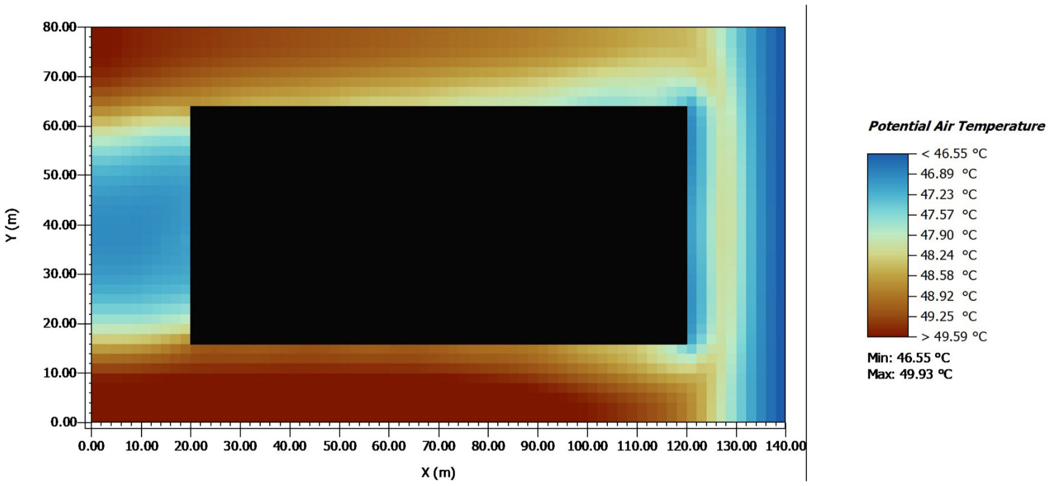


Figure 4.17: Microclimate results of White Paint scenario at 3pm, y = 180cm. *ENVI-met Leonardo*.

4.4.2. Air temperature measurements comparison for the different scenarios using the baseline scenario as a reference

The air temperature measurements provide a clear overview of heat patterns across different scenarios compared to the base. This allows for comparisons of how each scenario behaves, highlighting similarities and differences. Measuring temperatures at two heights adds a comprehensive perspective on what different people might experience. However, the graphs alone make it difficult to precisely assess the cooling effects. To address this, a follow-up analysis was conducted by layering each scenario onto the base and calculating the differences in air temperature. This approach provides a clearer understanding of the cooling impact of each scenario. Each visualization is printed out in 2D, pictured from above (helicopter view). The x- and y-axes represent the scale of the model, with the building being placed at the centre. The building is featured as a black rectangle ranging from 20 meters to 120 meters in the x direction and 15 meters to 65 meters in the y direction. Surrounding the building, is a temperature gradient which represent the temperature difference in neighbouring street between the retrofitting scenario being analysed, and the baseline. This dispersion ranges from blue, the smallest estimated temperature difference, and red, the largest estimated temperature difference. It is important to note that a negative value represents a decrease in temperature, while positive values represent an increase in temperature. Temperature measurements are predicted at 140cm above ground (z=1.40m), at 3pm.

Green Roof Scenario

In this scenario, 50% of the roof is covered with vegetation(figure 4.18). The prognosis estimates that the biggest decreases in temperature as a result of the proposed scenario will occur in the north-western region of the building. The maximum decrease is expected to be 0.76°C (ΔT = -0.76°C), directly in front of the north-facing wall. This cooling spreads further northwest and in the street adjacent to the west-facing wall. These temperature decreases are expected to range between 0.32 and 0.76°C. More modest temperature decreases are expected north-east. The south-facing wall registers only a modest temperature decrease, ranging between 0.05 and 0.23°C, similar to the street next to the east-facing wall. A slight temperature increase (up to 0.13°C) can be noted further towards the east (x = 140m). Important is to note that this region was consistently amongst the coldest area in all the presented scenarios.

Green Wall Scenario

In this scenario, 50% of the north-facing wall is covered with vegetation (figure 4.19). The prognosis estimates that, much like the green roof scenario, the biggest temperature decreases due to the proposed scenario will occur in the north-western region of the building at 0.85°C. However, contrary to the previous scenario, the localised spread of the cooling effect is predicted to be less pronounced: the west-facing wall is not cooled as much as in the previous scenario. While the west-facing wall was expected to experience an evident cooling factor in the last scenario, there appears to be a cooling ranging between 0.07 and 0.36°C, which corresponds to approximately only 30% of that predicted above. The other walls (south-facing wall and east-facing) appear to maintain a similar temperature fluctuation between both scenarios. A slight temperature decrease, ranging between <0.07 and 0.26°C, can be noticed in the street adjacent to the south-facing wall while a modest decrease in temperature, followed by a slight increase in temperature (ΔT = 0.13°C) towards the edge (x = 140m), is noted in the street adjacent to the east-facing wall.

Combination Scenario

In this scenario, 50% of the north-facing wall is covered with vegetation, as well as 50% of the roof (figure 4.20). This model predicts that the with this scenario, the maximal air temperature experienced would decrease by up to 1.08°C compared to the baseline model. This maximal temperature experienced would be perceived along the north-facing wall, while the cooling effect would be spread towards the north-west and along the west-facing wall. Minor cooling effect are still noticeable in the north-east, as well as along the south and east facing wall. These decreases sit between 0.12 and 0.36°C, making them generally more pronounced than either of the previous scenario alone. Again, a slight increase in temperature towards the edge (x = 140m) is predicted.

Reflective Coat Scenario

In this final scenario, the entire building is painted white (figure 4.21). Again, it is compared to the baseline scenario. The cooling effect fluctuates between ΔT = 0.14°C (a 0.14°C temperature increase) at the limit of the eastern street to ΔT = - 0.55°C along the north-facing wall. While the temperature difference is less pronounced in general, it appears to be more evenly distributed north of the building, particularly in the north-west, ranging from 0.27 to 0.55°C, the latter being the maximal-predicted temperature for this scenario. The west-facing wall experience a temperature decrease between 0.14 and 0.27°C when adding white paint. This cooling effect continues in the street facing the south-facing wall, which experience similar air temperature reduction. Once more, a slight increase in temperature towards the edge (x = 140m) is predicted.

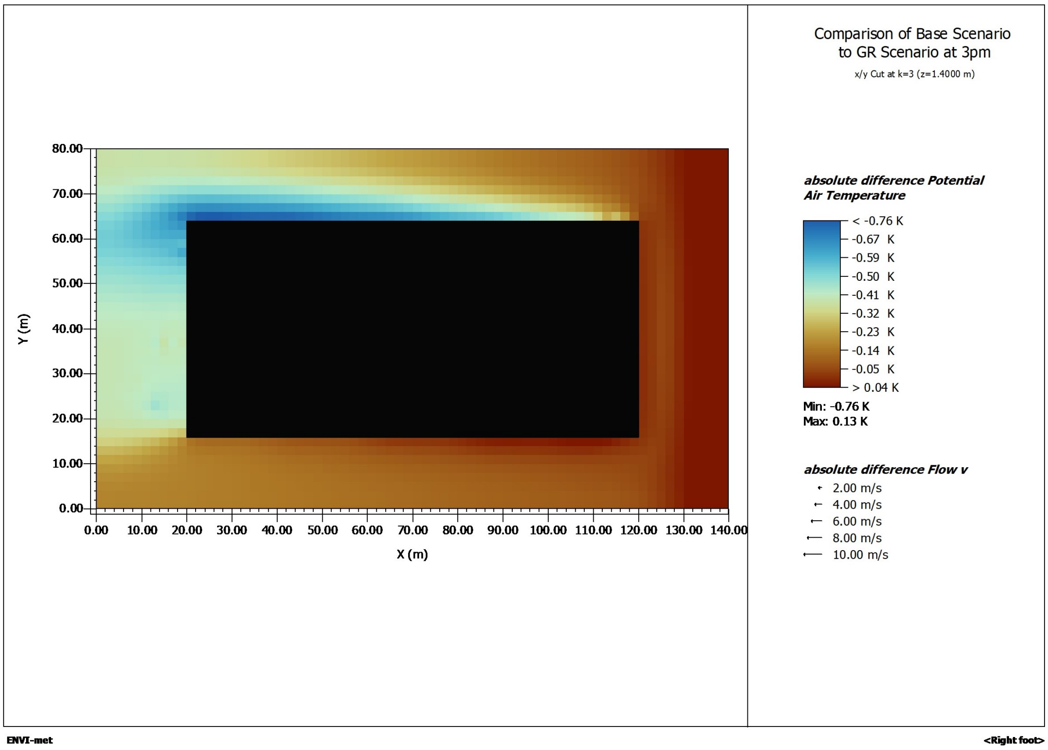


Figure 4.18: Comparison of Base Case to Green Roof Scenario at 3pm. The gradient signifies a decrease (negative values) or increase (positive values) of the studied scenario pertaining to the base scenario, ranging from most substantial cooling (dark blue) to least substantial cooling (dark red). *ENVI-met Leonardo*.

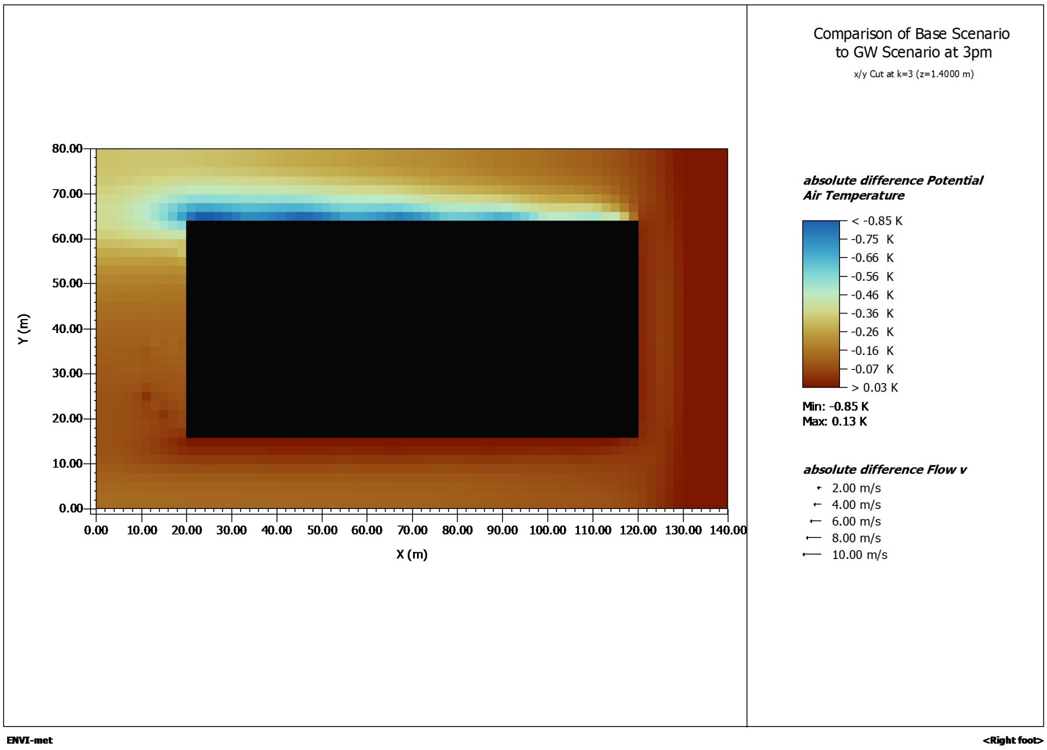


Figure 4.19: Comparison of Base Case to Green Wall Scenario at 3pm. The gradient signifies a decrease (negative values) or increase (positive values) of the studied scenario pertaining to the base scenario, ranging from most substantial cooling (dark blue) to least substantial cooling (dark red). *ENVI-met Leonardo*.

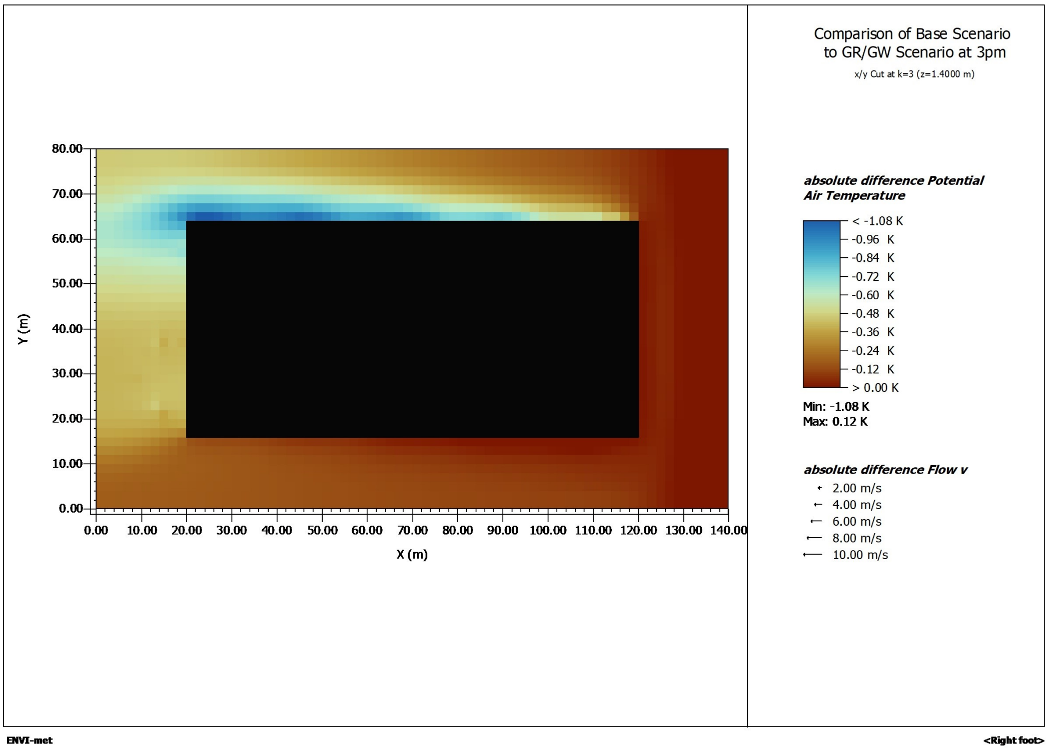


Figure 4.20: Comparison of Base Case to Combined Scenario at 3pm. The gradient signifies a decrease (negative values) or increase (positive values) of the studied scenario pertaining to the base scenario, ranging from most substantial cooling (dark blue) to least substantial cooling (dark red). *ENVI-met Leonardo*.

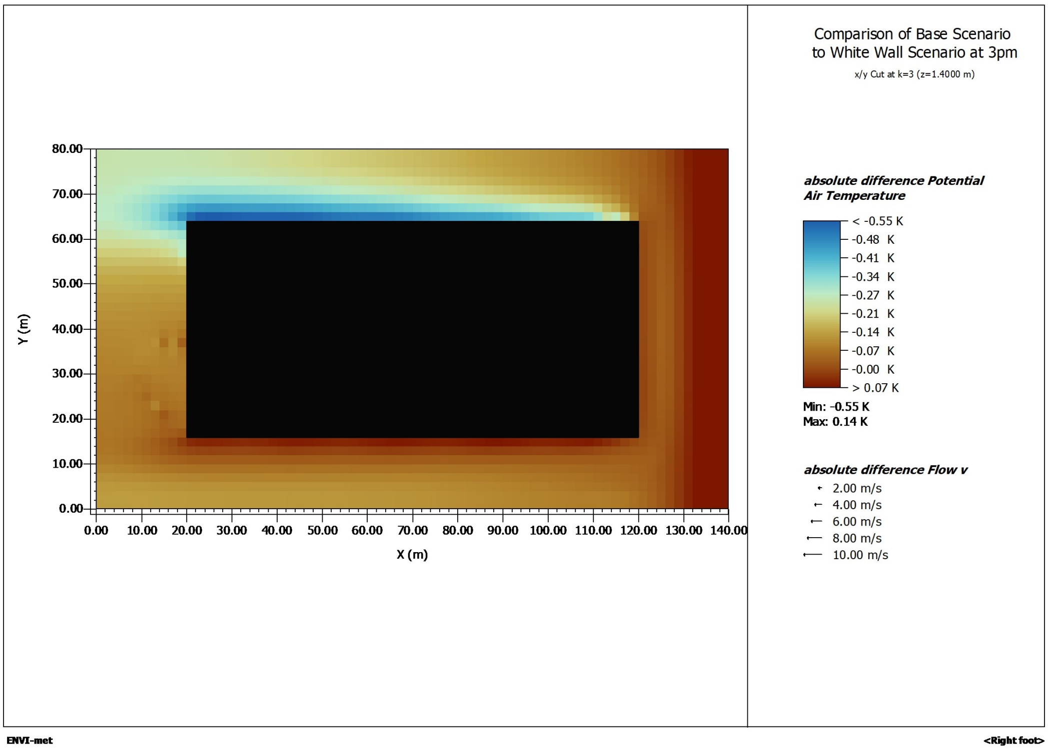


Figure 4.21: Comparison of Base Case to White Paint Scenario at 3pm. The gradient signifies a decrease (negative values) or increase (positive values) of the studied scenario pertaining to the base scenario, ranging from most substantial cooling (dark blue) to least substantial cooling (dark red). *ENVI-met Leonardo*.

4.4.3. Air temperature measurements for different scenarios at different times

To account for time sensitivity, the difference in air temperature between the different retrofitted scenario and the baseline is examined at two other times: 8am and 10pm. These new times help evaluate how the scenarios perform under different sunlight and temperature conditions. At 8am, the analysis assesses performance without long-term sun exposure or accumulated heat. At 10pm, it examines whether the scenarios have any impact when there is no direct sunlight.

Each visualization is printed out in 2D, pictured from above (helicopter view). The x- and y-axes represent the scale of the model, with the building being placed at the centre. The building is featured as a black rectangle ranging from 20 meters to 120 meters in the x direction and 15 to 65 meters in the y direction. Surrounding the building, is a temperature gradient which represent the temperature difference in neighbouring street between the retrofitting scenario being analysed, and the baseline. This dispersion ranges from blue, the smallest estimated temperature difference, and red, the largest estimated temperature difference. It is important to note that a negative value represents a decrease in temperature, while positive values represent an increase in temperature. All four comparisons made above were made at 3pm, thus not accounting for the dynamic nature of the microclimate. To account for that, a time sensitivity analysis is performed to reveal how these interventions perform under changing sunlight conditions, each scenario is reproduced at two different times of the day: 8 am and 10 pm. Again, temperature measurements are predicted at z=1.40m.

8am

These simulations seek to analyse how the same scenarios are impacted by varying climate conditions. Particularly, it assesses the functionality of each of the proposed solutions to consider how variations in sun direction throughout the day and seasons influence passive cooling strategies, through the placement of vegetation. To achieve this, the impact of the different scenarios towards its microclimate are studied at 8am. Each scenario is compared to the base case in the same way done above. The various graphs show the difference in temperature when applying a specific scenario, from the base case.

Green Roof Scenario

In this scenario, 50% of the roof is covered with vegetation. Cooling ranges from 0.11 to 0.88°C, and no (minor) heating is recorded at any location (figure 4.22). The largest cooling occurs in the north-west, as well as in the street adjacent to the west-facing wall, showcasing a relatively large propagation of the cooling effect. The temperature decrease ranges from 0.57 to 0.88°C in these areas. The least amount of cooling is observed in the part of the street directly adjacent to the south-facing wall (y=15m) and at the edges of the street adjacent to the east facing wall. This is subsequently also the location where the minimum temperature decrease of 0.11°C is observed. Finally, moderate cooling (between 0.34 to 0. 50°C) is predicted in the north-east, as well as street facing the eastern wall and at the edge of street across the south-facing wall.

Green Wall Scenario

In this scenario, 50% of the north-facing wall is covered with vegetation. Cooling ranges from 0.11°C to 1.19°C (figure 4.23). The largest cooling is observed in the street adjacent to the north-facing wall, with temperature decreases ranging from 0.87 to 1.19°C, but the cooling effect remains very contained and mostly local to this fragment. This is not surprising as this is where the green walls are located. It is further unsurprising that the highest levels of cooling are predicted to be in the force of 'cool pockets' directly in front of the various fragments of vegetation on the wall. The least amount of cooling is on the street adjacent to the west-facing wall, as well as on the edge of the street opposite the south-facing wall (y = 0 to 10m). These temperature changes ranges from 0.11 to 0.43°C. Finally, a temperature increase can be noted in the part of the street directly in front of the south-facing wall (y = 15m), as well as in the street opposite the south-facing wall.

Combination Scenario

In this scenario, both the north-facing wall and the roof of the building are covered with 50% vegetation (figure 4.24). Cooling ranges from 0.11 to 1.31°C, signifying a very pronounced cooling effect, with a large and intense propagation The largest amount of cooling is predicted to be in the north-west direction, with temperature decreases ranging between 0.95 and 1.31°C. The cooling further spread to the surrounding area: a 0.71°C decrease is visible in the west-facing fall, as well as a decrease of 0.47°C along the north-facing wall. The lowest amount of cooling is observed in the part of street directly adjacent to the south-facing wall (y=15m) and the edge of street of the east-facing wall (x = 140m). The temperature decrease observed in these areas can fall as low as 0.11 to 0.23°C.

Reflective Coat Scenario

In this scenario, the entire building is covered in white paint, but no vegetation is added. With this scenario, cooling ranges from 0.11 to 0.75°C compared to the base case, signifying a pronounced cooling effect (figure 4.25). Despite the propagation being less pronounced than with other scenarios, namely those which include roof vegetation, cooling is not strictly localised. The highest cooling is visible in the north-western direction, with temperature decreases ranging between 0.56 and 0.75°C. Cooling spread to the surrounding area, towards the north-east. In this area, the decrease in temperature ranges between 0.56 and 0.68°C decreases. However, the cooling is more limited in the direction of the west-facing wall, at approx. 0.30°C. The least amount of cooling is observed in the street directly adjacent to the south-facing wall, at y = 15m, as well as in the southern part of the west-facing wall (y = 0 to 40m), and the edge of the street of the east-facing wall (x = 140m). The minimum air temperature decrease in these areas ranges between 0.11 and 0.17°C. Finally, moderate cooling (0.30 to 0. 49°C) is observed in the street opposite the east-facing wall, and the edge of the street across the south-facing wall (y = 0m).

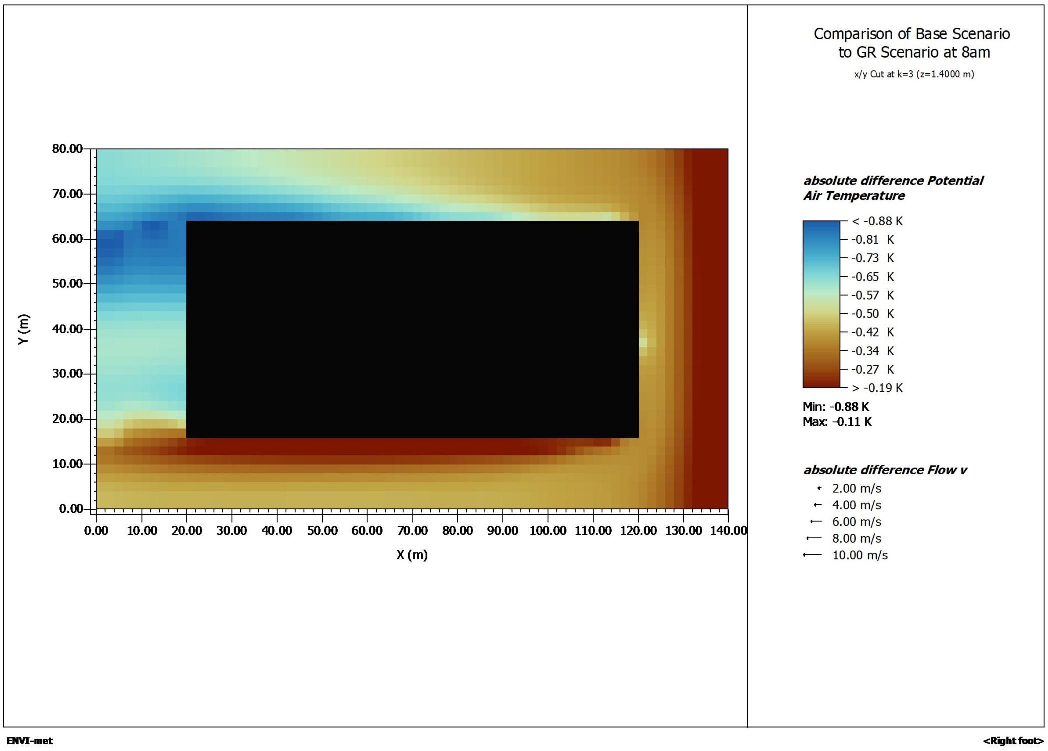


Figure 4.22: Comparison of Base Case to Green Roof Scenario at 8am. The gradient signifies a decrease (negative values) or increase (positive values) of the studied scenario pertaining to the base scenario, ranging from most substantial cooling (dark blue) to least substantial cooling (dark red). *ENVI-met Leonardo*.

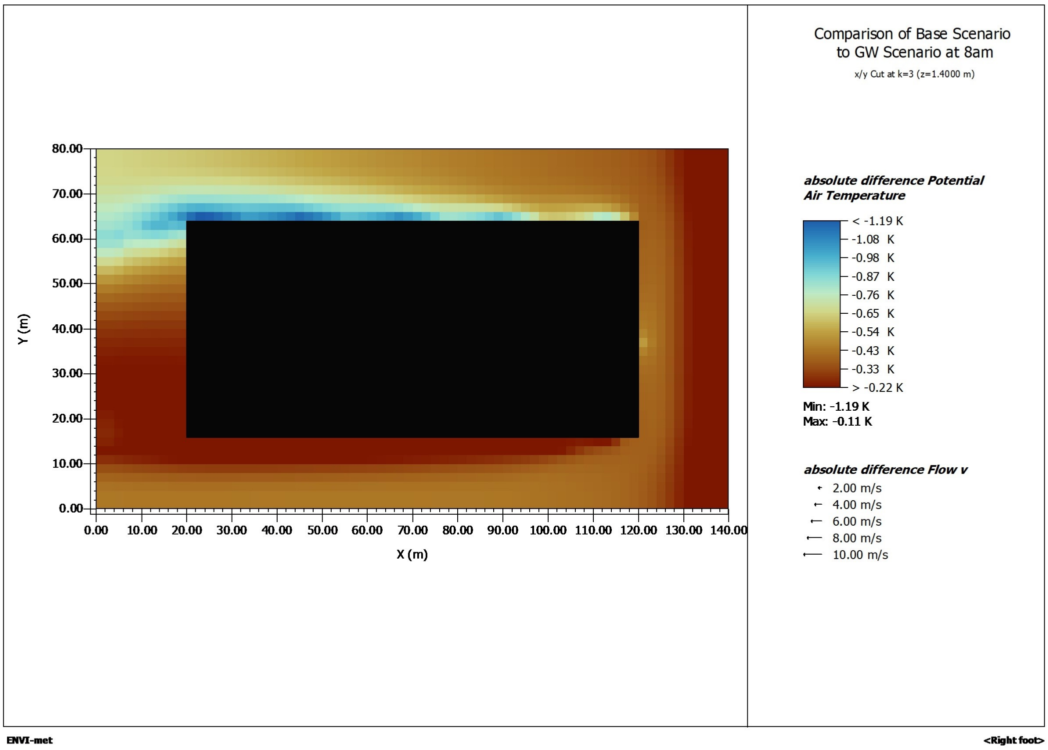


Figure 4.23: Comparison of Base Case to Green Wall Scenario at 8am. The gradient signifies a decrease (negative values) or increase (positive values) of the studied scenario pertaining to the base scenario, ranging from most substantial cooling (dark blue) to least substantial cooling (dark red). *ENVI-met Leonardo*.

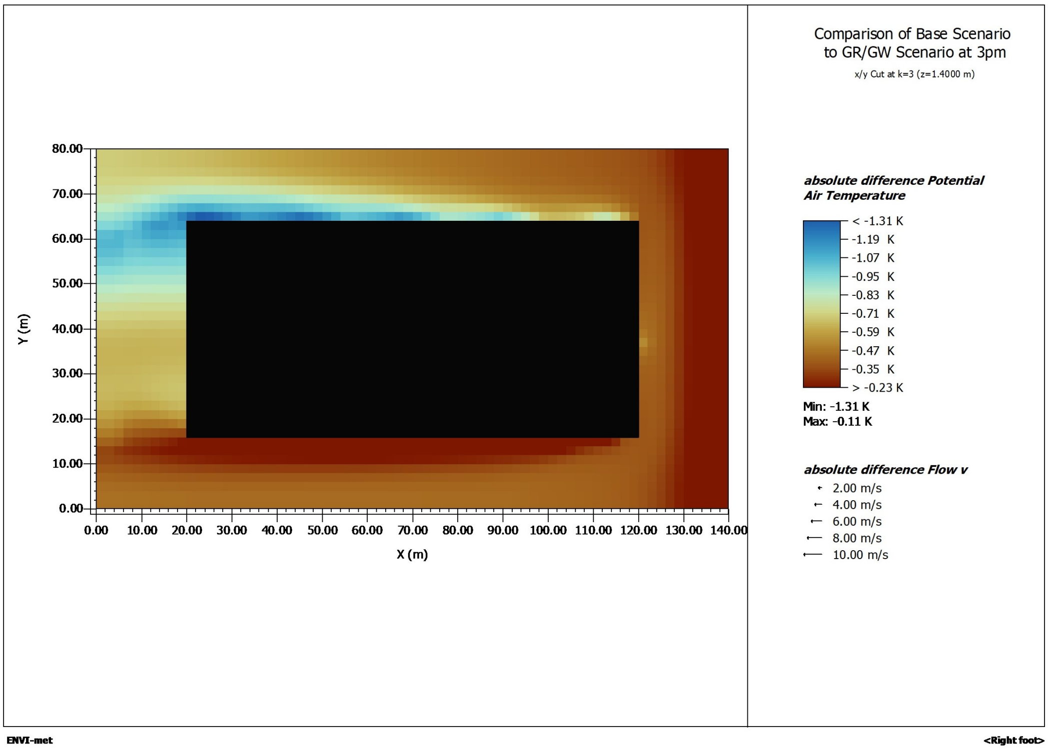


Figure 4.24: Comparison of Base Case to Combined Scenario at 8am. The gradient signifies a decrease (negative values) or increase (positive values) of the studied scenario pertaining to the base scenario, ranging from most substantial cooling (dark blue) to least substantial cooling (dark red). *ENVI-met Leonardo*.

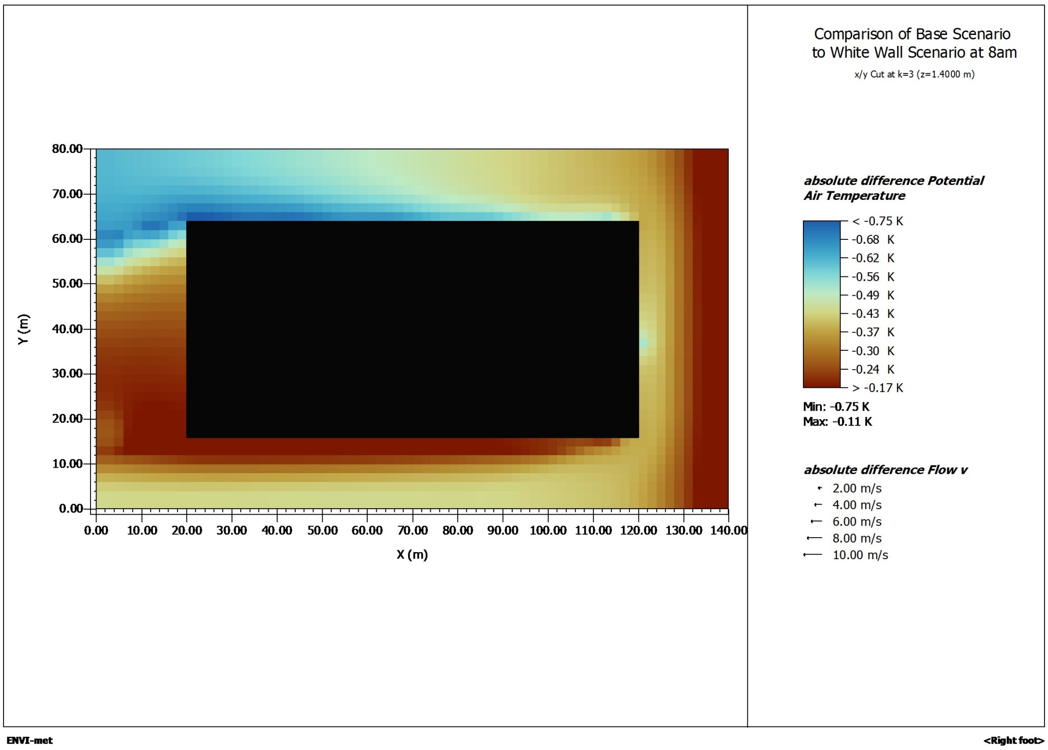


Figure 4.25: Comparison of Base Case to Combined Scenario at 8am. The gradient signifies a decrease (negative values) or increase (positive values) of the studied scenario pertaining to the base scenario, ranging from most substantial cooling (dark blue) to least substantial cooling (dark red). *ENVI-met Leonardo*.

10pm

To further assesses the functionality of each of the proposed solutions in different conditions, a simulation is proposed at night, in absence of sunlight. To achieve this, a simulation is run at 10pm at night for each of the cases. Each scenario is compared to the base case in the same way done above.

Green Roof Scenario

In this scenario, 50% of the roof is covered with vegetation. Cooling now ranges from 0.01 to 0.22°C, which can be considered minimal (figure 4.27). The cooling is most pronounced in the street adjacent to the west-facing wall, and some fragments along the north-facing fall. Moderate cooling, between 0.09 and 0.11°C, is predicted in the northwest, while the effect on and near the south and east-facing walls can be described as negligible (0.01 to 0.03°C).

Green Wall Scenario

In this scenario, 50% of the north-facing wall is covered with vegetation. In this scenario, cooling remains minimal, although more pronounced than in the previous scenario, now ranging from -0.01 (minor temperature increase) to 0.40°C (figure 4.26). This maximum temperature is recorded along the north-facing wall, in the form of pockets. These pockets' spacing corresponds to the green walls' exact spacing. The cool of these pockets does appear to project slightly within their surroundings, mostly in the northwestern direction, where the projected cooling, pertaining to the base scenario, falls to 0.19°C. This indicates that, within the context of this simulation, vegetation has a cooling function after sundown, but only within a limited sprawl. The other walls, which contain no vegetation at all, experience trivial cooling (<0.10K) walls.

Combination Scenario

In this scenario, both the north-facing wall and the roof of the building are covered with 50% vegetation (figure 4.28). This scenario appears to be a near-perfect overlay between the two previous scenarios. Cooling ranges from 0.00°C, which signifies neither cooling nor heating compared to the baseline, while the highest recorded cooling is measured to sit at 0.43°C. The pockets on the north-facing wall are still visible and are complemented with additional cooling on the west-facing wall, which observed a decrease in air temperature of approx. 0.17 to 0.21°C. The other walls continue to experience trivial cooling (<0.10K).

Reflective Coat Scenario

In this scenario, the entire building is covered in white paint, but no vegetation is added (figure 4.29). The results of this run are very interesting as the temperature gradient, which has until now remain fairly consistent between different scenarios, is quite different from what was observed previously. However, the overall cooling is very much negligeable, ranging from 0.00°C to 0.11°C. Most of the cooling that does occur take place on the north-facing wall, the northwest and the southwest, but the predicted cooling is set to range between 0.08 to 0.11°C. The least amount of cooling will occur in the south and east direction, with a maximal prediction of 0.04°C.

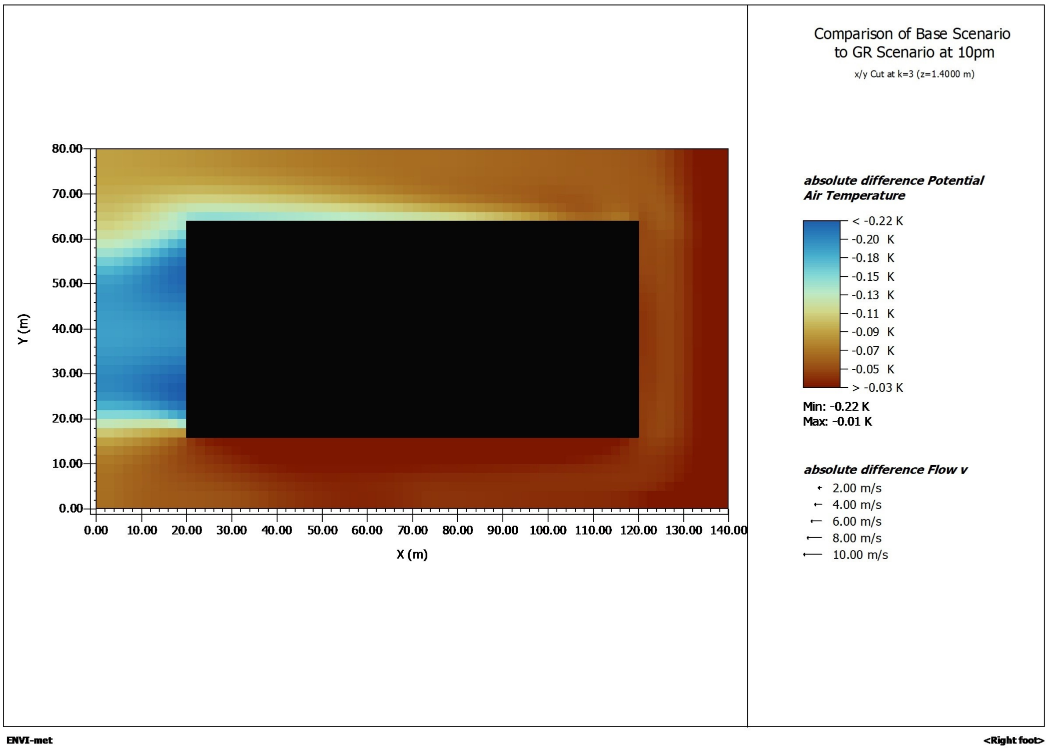


Figure 4.26: Comparison of Base Case to Green Roof Scenario at 10pm. The gradient signifies a decrease (negative values) or increase (positive values) of the studied scenario pertaining to the base scenario, ranging from most substantial cooling (dark blue) to least substantial cooling (dark red). *ENVI-met Leonardo*.

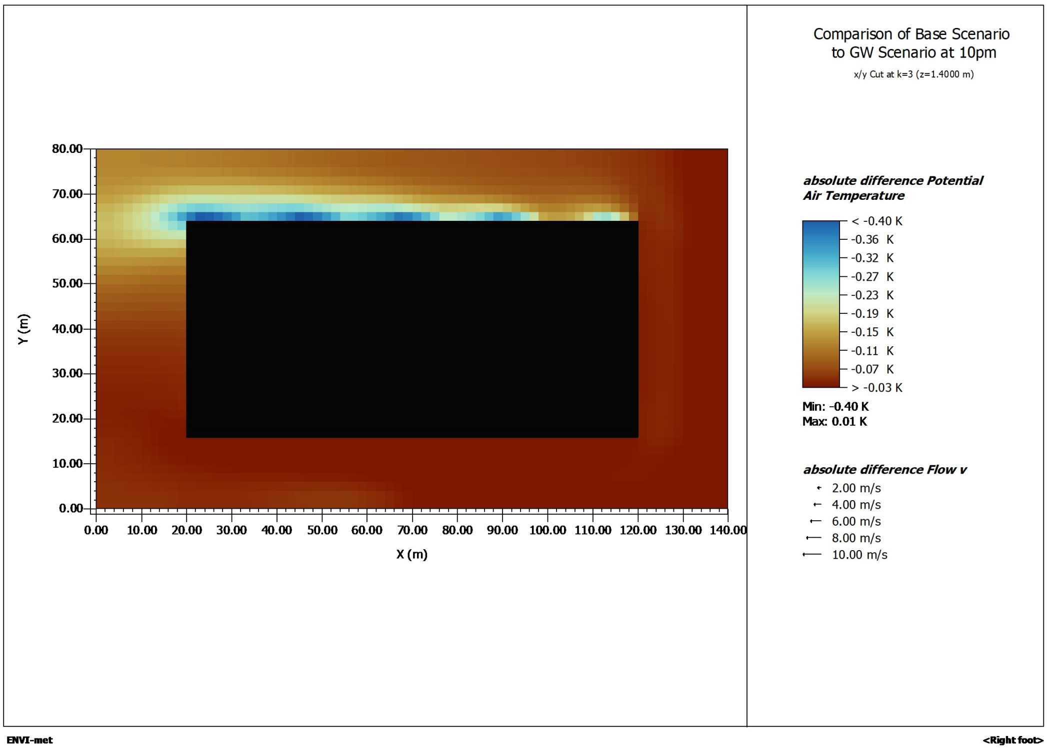


Figure 4.27: Comparison of Base Case to Green Wall Scenario at 10pm. The gradient signifies a decrease (negative values) or increase (positive values) of the studied scenario pertaining to the base scenario, ranging from most substantial cooling (dark blue) to least substantial cooling (dark red). *ENVI-met Leonardo*.

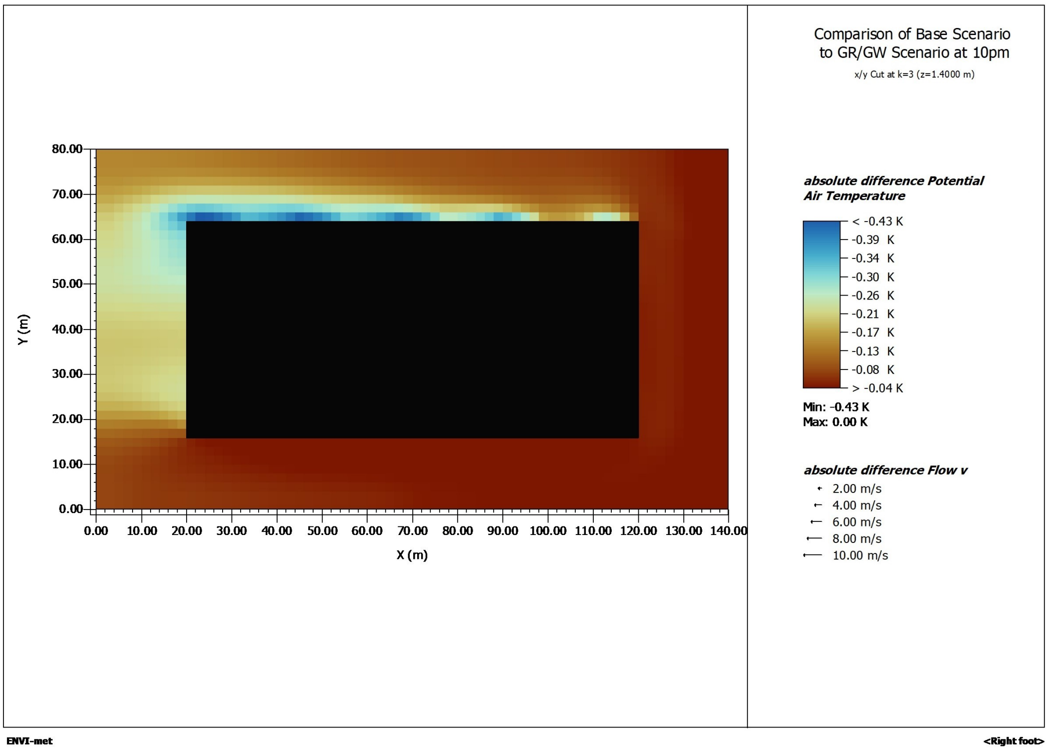


Figure 4.28: Comparison of Base Case to Combined Scenario at 10pm. The gradient signifies a decrease (negative values) or increase (positive values) of the studied scenario pertaining to the base scenario, ranging from most substantial cooling (dark blue) to least substantial cooling (dark red). *ENVI-met Leonardo*.

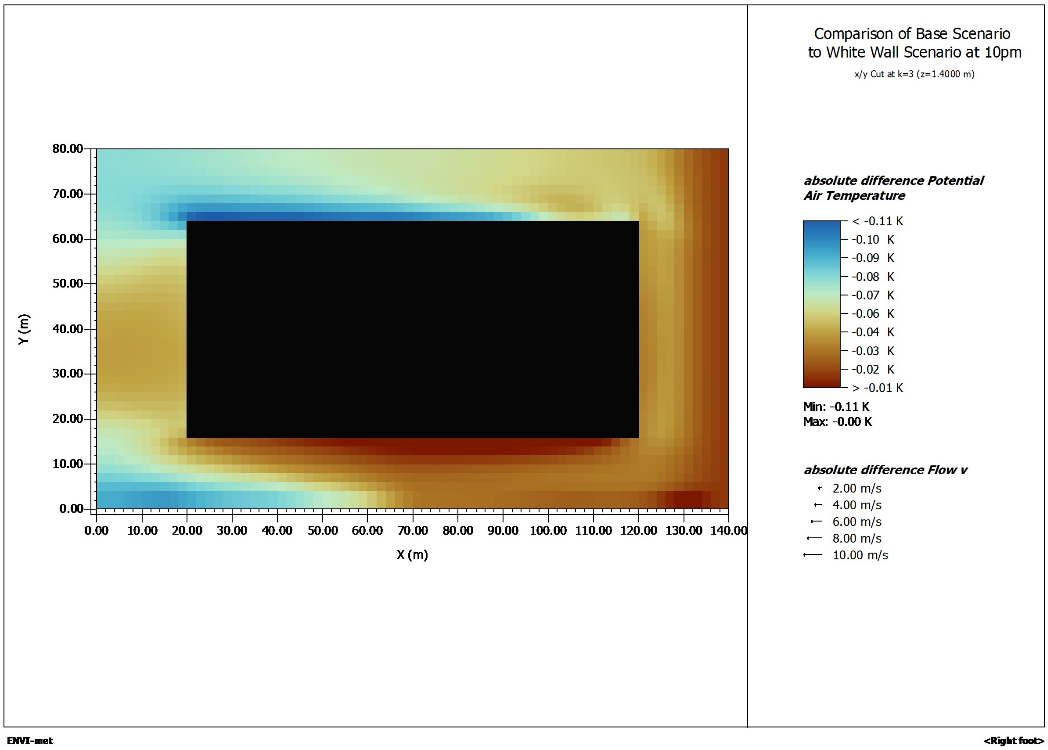


Figure 4.29: Comparison of Base Case to Combined Scenario a at 10pm. The gradient signifies a decrease (negative values) or increase (positive values) of the studied scenario pertaining to the base scenario, ranging from most substantial cooling (dark blue) to least substantial cooling (dark red). *ENVI-met Leonardo*.

4.4.4. Core Findings

The analysis of perceived temperatures around a building reveals how different design interventions can impact temperature variations throughout the day. First, the impact of the different scenarios on the micro-climate around the building is measured at 140 cm above ground (about the size of a child), at 3pm. The baseline scenario (no roofs, no wall, no coating) shows significant temperature differences across the building surface. Air temperature in this scenario reaches a high of 50.3°C and falls down to 46.83°C. South-facing walls are consistently warmer, maintaining a temperature at around 49°C, while north-facing walls seem to vary more, from 47.5°C to 49°C. The coolest temperatures are found along east-facing walls, where they hover around 47°C, though nearby street areas show some fluctuations.

Adding green roofs to 50% of the building area yields a slight cooling effect, reducing the maximum air temperature to 50.17°C and the minimum to 46.68°C. This cooling is most noticeable on the north-facing wall, where temperatures now range from 47°C to 48.5°C, representing a decrease of roughly 0.5°C. Additionally, the west-facing wall sees a slight temperature reduction, resulting in an overall air temperature of just above 46.5°C. When green walls are added specifically to the north-facing wall, the temperature dispersion pattern shows only minimal cooling effects, similar to the green roof scenario alone. However, combining green roofs and green walls on the north-facing wall produces a slightly more pronounced cooling effect, though the temperature dispersion and overall impact remain comparable to green roofs alone. Painting the walls white has the least effect on temperature, maintaining a high of 50.19°C and a low of 46.96°C, with dispersion patterns similar to the green wall scenario. Moving up to 180 cm above ground (about the height of an adult male), temperature patterns are consistent with those observed at 140 cm, though they tend to be slightly cooler. The baseline scenario at this height ranges between 46.39°C and 50.04°C. None of the interventions significantly lower the minimum temperature, but all managed to reduce the maximum by less than 0.15°C. This results in a narrower temperature range around the building at this height.

A comparison across different times of day (8 am, 3 pm, and 10 pm), at 140 cm above ground reveals how these interventions perform under changing sunlight conditions. At 8 am (figure 14), the combined efforts of green roofs and green walls have the most substantial cooling effect, reducing temperatures by up to 1.31°C in the northwest direction, while the lowest reduction of 0.11°C occurs near the south-facing wall. The white wall scenario shows the smallest absolute reduction (0.75°C) but maintains a rather broad area of impact.

By 3 pm, the combined green roof and green wall scenario achieves the most notable temperature reduction from all the scenarios, cooling certain localized areas by up to 1°C. The green roof, green wall, and combined green roof-green wall scenario demonstrate similar cooling patterns around the building, with temperature reductions ranging from 0.6 to 1°C. The white wall scenario again has the least impact, with maximum reductions between 0.15°C and 0.55K. Finally, at 10 pm (figure 15), all scenarios exhibit much lower cooling patterns. However, the temperature distribution across the interventions is the most pronounced. The combined green roof and green wall scenario cools the most, with a 0.4°C reduction compared to the baseline, while the white wall scenario shows the smallest impact, with only a 0.11K decrease. As expected, cooling effects are minimal at night due to the absence of sunlight.

Despite results showcasing clear cooling effects, most interventions feature slight temperature increases in certain localised areas. These increases lay at around 0.10 to 0.15°C. These increases are minor, and can thus be considered insignificant.

Time	Scenario	Maximum Cooling (K)	Minimum Cooling/Maximum Heating (K)	Heating (Yes/No)
8am	GR	-0.88	-0.19	No
8am	GW	-1.19	-0.11	No
8am	COMBO	-1.31	-0.11	No
8am	WHITE	-0.75	-0.11	No
3pm	GR	-0.76	0.13	Yes
3pm	GW	-0.85	0.13	Yes
3pm	COMBO	-1.08	-0.12	No
3pm	WHITE	-0.55	0.14	Yes
10pm	GR	-0.22	-0.01	No
10pm	GW	-0.40	0.01	Yes
10pm	COMBO	-0.43	0.00	No
10pm	WHITE	-0.11	0.00	No

Table 4.1: Results of the comparative analysis of scenarios. Negative values indicate cooling, while positive values indicate heating. GR: Green Roof scenario; GW: Green Wall scenario; COMBO: Combined green roofs and green walls scenario; WHITE: Reflective white paint.

Research in humid and tropical regions, particularly in Iran and Singapore, has examined the effects of green roofs or walls adjacent to these types of infrastructure. Qin et al. (2012) built a green roof test bed at Nanyang Technological University in Singapore and monitored the temperature differences resulting from this installation compared to a bare roof. They found that in their scenario, green roofs reduced the surface temperature of the roof by up to 7.3ºC and the ambient air temperature by 0.5ºC. Baghaei et al. (2021) modelled an existing building in Rasht, Iran, using EnergyPlus and ENVI-met, and validated the obtained data with field measurements. They found that green walls can reduce the temperature in front of the wall by up to 0.36ºC, which they deemed insignificant. The results obtained from this prior research show similar magnitudes to those observed in the simulation runs mentioned above. However, the modeling performed in the context of Riyadh shows somewhat better results overall, which could be attributed to the specific climate. In their 2005 research, Priyadarsini and Wong assessed the effects of black and white aluminum façades on surface and ambient air temperatures within urban canyons in the Central Business District area of Singapore. They found that, systematically, both the surface and ambient air temperatures were lower when using white façades, with ambient temperature reductions of up to 2.5ºC, which they considered to be desirable results. The research concluded that this is a valuable strategy for mitigating localized heat. Comparatively, in research conducted using the city of Riyadh as an example, white coatings achieved significantly lower results. The maximum recorded reduction in temperature for the various time tests was 0.75ºC, representing only 30% of the results obtained in the earlier studies. Relatively, these results are therefore less substantial.

5

Discussion

5.1. Interviews

Following the interviews with the experts, several structural challenges were brought to light, undercutting the feasibility of green roofs and façades in arid climates. Green roofs require **deeper soil layers**, around 50 cm, to withstand extreme solar radiation and retain moisture. This significantly increases the weight load, making them structurally challenging for existing buildings, which would need costly retrofitting and structural reassessments. In contrast, green walls are less structurally demanding since they do not rest directly on buildings. Instead, they can ”hover” over existing structures, providing a more practical and adaptable alternative. Furthermore, the importance of **proper plant selection**, who require to be suitable for the extreme climate of such regions, was brought up by several experts. Vegetation in Riyadh must withstand extreme summer temperatures of up to 50°C and occasional heavy rainfall, making drought-resistant plants like lavender, mint, and oregano ideal choices. However, these plants absorb atmospheric humidity, which could worsen the city’s already arid conditions. To mitigate this, frequent irrigation may be required to promote evapotranspiration, though this raises concerns about **water sustainability**. Additionally, the limited capacity of local nurseries creates logistical challenges in sourcing suitable plants, further complicating the implementation of green infrastructure.

Despite these challenges, experts suggested urban design and implementation strategies to make such interventions both practical and effective. Green walls should ideally **face north** to minimize direct sunlight exposure, protecting plants from overheating and lowering water requirements. Slow-growing, **drought-resistant species** are preferred to reduce pruning and maintenance, though their limited availability may pose challenges. **Early collaboration** with urban planners and engineers is essential to ensure that green infrastructure integrates seamlessly with the city’s broader urban design and sustainability goals. The relative cost, maintenance, and effectiveness of green roofs and walls must be weighed against alternative solutions, such as reflective coatings or shading structures. Resource-intensive retrofitting processes and the need for specialized design elements may limit the scalability of green infrastructure unless substantial environmental or social benefits can be demonstrated. However, many maintain concerns about the **cost-effectiveness** of green roofs and walls compared to simpler alternatives like reflective white paint, which provides cooling benefits with minimal maintenance and expense. Interestingly, this concern sit in stark **contrast with prior literature** (cited in the literature review), claiming green roofs as a cost-effective alternative. Drawing conclusions from expert interview, a more balanced approach to urban cooling could combine green infrastructure with reflective surfaces and natural shading through structural elements, such as concrete overhangs, to maximize efficiency and cost-effectiveness.

Finally, all experts agreed that green infrastructure should be designed to align with Riyadh’s broader environmental and urban development strategies, addressing both long-term sustainability and immediate urban cooling needs. Policymakers could introduce incentives for incorporating green roofs and walls, particularly in new construction projects, to gradually build the capacity and adoption of such initiatives over time.

5.2. Model Preparation

The model was developed by integrating findings from interviews, literature, fieldwork, and remote sensing. Remote sensing was used to gain a better understanding of Riyadh ecosystem, and how its aspect influences temperature at a city-wide scale. The observation of satellite images informed the general shape and orientation of the building, while details such as material composition (concrete) and window-to-wall ratio (13%) were established through literature and validated by field observations. Scenarios for the study were informed by interview findings, which shaped decisions on wall orientation and the inclusion of alternative cooling solutions, ensuring the model reflected practical and context-specific insights.

5.3. Framework and Model

The combined green roof and green wall (GR/GW) scenario provides the most significant cooling effect, reducing localized temperatures by up to 1°C at 3 pm. This demonstrates the enhanced **effectiveness of combining multiple interventions**. The GR/GW scenario consistently outperforms individual measures, showing that integrated solutions are more effective than standalone ones. However, the cooling effects of green roofs and walls are highly localized, making them better suited for improving microclimates rather than reducing temperatures on a citywide scale. In comparison, white-painted walls (high reflectivity) have a smaller cooling impact, reducing temperatures by 0.15°C to 0.55°C. Despite their lower effectiveness, they are generally more cost-effective and easier to implement.

Height-specific temperature variation appears to be only marginal. At 180 cm, temperatures are slightly cooler, suggesting that cooling effects vary with height and proximity to ground surfaces, such as heat radiating from streets. However, temperature patterns at both heights remain largely consistent, indicating limited vertical variation in cooling effects for the tested interventions. By measuring temperatures at multiple heights, the study ensures that thermal comfort is assessed for different demographic groups, such as children and adults. This human-centred approach aligns the analysis with real-world thermal comfort considerations.

Finally, a **time-of-day sensitivity analysis** assessed the effectiveness of the proposed methods under differing sunlight conditions. At 8 am, green roofs demonstrate the largest cooling effect, reducing temperatures by up to 0.88°C. The combined green roof and green wall (GR/GW) scenario performs even better, reducing temperatures by up to 1.31°C. However, these cooling effects are unevenly distributed, with minimal reductions (0.11°C) observed on south-facing walls. White walls provide the smallest overall temperature reduction (0.75°C) but maintain a broader and more uniform cooling effect. This highlights the potential of reflective surfaces to deliver consistent, though modest, cooling benefits. As expected, cooling effects at night are minimal due to the absence of solar radiation. The GR/GW scenario achieves the largest nighttime reduction (0.4°C), while white walls have the smallest impact (0.11°C). These results emphasize the limited nighttime benefits of interventions designed primarily to counter solar-generated heat rather than residual heat stored in urban materials. The time-of-day analysis shows that cooling strategies are **most effective during peak solar radiation hours**, underscoring the need for complementary measures, such as improved ventilation or hybrid cooling systems, to tackle nighttime heat retention.

Prior research has examined the effects of green roofs, walls, or reflective paint on the ambient air temperature adjacent to the buildings where these infrastructures are implemented, focusing on humid regions like Iran and tropical regions like Singapore. Qin et al. (2012) found that ambient air temperature around their green roof test bed was reduced by 0.5ºC compared to a bare roof in a tropical climate, while Baghaei et al. (2021) found that green walls can reduce the temperature in front of the wall by up to 0.36ºC in humid climate. In their research, Baghaei et al. (2021) argued that this result was insignificant. Comparatively, green roofs were found to be able to help reduce ambient temperature by up to 0.88ºC at 8am, while green walls were able to help reduce temperature by up to 1.19ºC, also at 8am. The results found in the study of Riyadh are thus in the same order of magnitude, but still imply a greater cooling performance. Research by Priyadarsini and Wong (2005) found that white aluminium coating was able to reduce ambient temperature reductions of up to 2.5ºC as compared to black aluminium, and considered these results to be significant. Comparatively, white paint appeared to achieve significantly lower results compared to a bare housing block, which can most likely be attributed to a difference in the coating material. The maximum recorded reduction in temperature for white paint was

0.75ºC, making the results less substantial.

Research by the CMCC indicates that **humans can notably perceive temperature change of 1°C**, but are less perceptive to a temperature change below that (Mazzai, 2023). The minimum temperature difference fully perceptible by humans being 1°C would makes green roofs and white paint largely inefficient based on the tests in this research, as the recorded reductions were below this threshold. However, the combination of green roofs and walls proved to be the most effective, consistently achieving temperature decreases greater than 1°C during both daytime test periods.

5.4. Impact

5.4.1. Societal Impact

This study emphasizes the importance of equitable urban design by assessing thermal comfort across different demographic groups, including children and outdoor workers. By measuring temperatures at heights of 140 cm (child height) and 180 cm (adult height), the research highlights the need for urban environments that cater to diverse societal segments, enhancing overall liveability and inclusivity. The findings underscore the effectiveness of targeted cooling interventions, such as green roofs, green walls, and reflective white walls, in providing localized cooling around buildings. These strategies not only reduce heat exposure for pedestrians and residents but also contribute to improved urban walkability, higher outdoor activity levels, and enhanced well-being.

Even marginal cooling effects, such as reducing peak temperatures by up to 1°C, can significantly alleviate heat stress during peak afternoon hours—critical periods when health risks are at their highest. This has a direct impact on public health by mitigating heat-related illnesses and improving overall health outcomes. Additionally, the reduction of air temperatures around buildings offers indirect benefits, such as lowering energy demands for cooling. This translates to decreased electricity costs for households and businesses, fostering economic resilience and long-term sustainability.

5.4.2. Scientific Impact

This research explores how building designs influence microclimates in arid environments by analysing temperature variations at child and adult heights, as well as at different times of the day. These insights add valuable data to the study of urban heat island (UHI) mitigation. By quantifying cooling effects, such as temperature reductions of up to 1.08°C in localized areas at 3 pm, and even higher in the morning, the study provides a scientific base for evaluating green roofs, green walls, and reflective surfaces. This precise data makes it easier to replicate and scale these solutions in other cities.

The research also compares temperature patterns in the morning, afternoon, and evening, showing how interventions perform under different sunlight conditions. This time-based approach deepens our understanding of how solar radiation interacts with design features and helps in planning effective, time-sensitive solutions. Additionally, the findings confirm existing ideas, such as the limited effectiveness of interventions at night when sunlight is absent.

The mixed-method approach, which includes height-specific analysis, temperature dispersion patterns, and expert interviews, offers a useful framework for future studies and can easily be generalizable. It allows for testing new materials and interventions, contributing to more effective urban design strategies.

5.4.3. Policy Impact

Policymakers can use these findings to prioritize interventions that offer the most significant cooling benefits, such as combining green roofs and green walls. This evidence-based approach enables more informed urban planning and supports climate adaptation strategies. The measurable benefits of green roofs and walls, even in extreme climates, highlight their value for inclusion in building regulations and green certification programs. Specific guidelines could encourage or mandate green infrastructure through climate-responsive building codes.

The study's analysis of wall orientations, such as the consistently warmer south-facing walls that limit vegetation options, emphasizes the need for design-specific policies. For example, incentive programs could focus on shading these walls, where cooling is most needed. Even minimal cooling effects observed in this study support national energy efficiency goals by reducing the need for mechanical cooling. Policymakers can incorporate these findings into broader climate action plans, linking urban heat mitigation with energy conservation efforts. The research underscores the scalability of green infrastructure in arid climates. For regions pursuing comprehensive climate resilience policies, such as Saudi Vision 2030, these findings reinforce the importance of integrating microclimate-focused solutions into urban resilience strategies.

Finally, while nighttime cooling effects are limited, the study highlights the need for complementary policies. These could include promoting natural ventilation or hybrid cooling systems to enhance nighttime heat resilience.

5.5. Future Implementation

The findings demonstrate that green roofs and walls can reduce temperatures by up to 1.31°C in the immediate vicinity of buildings, offering a modest but tangible cooling benefit. However, implementing these solutions in arid climates, such as Riyadh, faces several practical, environmental, and structural challenges.

5.5.1. Structural Challenges

Green roofs require deeper soil layers to effectively buffer heat, which adds significant weight to the building. This necessitates thorough structural evaluations, especially when retrofitting older buildings, to ensure they can support the additional load. Green walls, on the other hand, do not always need to be attached to buildings and can function as standalone structures. However, their placement is often limited by site-specific conditions and design constraints. Retrofitting efforts are further complicated by the frequent lack of original building documentation. In such cases, costly structural recalculations may be needed, adding to the complexity of implementation. Green roofs present several challenges, starting with competition for space with HVAC infrastructure, which is typically prioritized on rooftops. Additionally, when waterlogged, green roofs become extremely heavy, with water weighing approximately 1,000 kilograms per cubic meter, posing significant structural concerns.

Cost is another critical issue. Rooftops are often out of sight and are more commonly utilized for revenue-generating purposes, such as parking spaces. For private investors, the high installation and maintenance costs of green roofs offer little financial return, making them an unattractive option without clear economic or regulatory incentives.

5.5.2. Plant Selection and Maintenance

Drought-resistant plants are essential for arid climates, but their tendency to absorb humidity from the air can further lower already low relative humidity levels, potentially reducing overall thermal comfort despite providing localized cooling. Most green roofs and walls require regular irrigation to survive, which poses a significant challenge in water-scarce environments. This conflict between water scarcity and maintenance needs makes widespread adoption less practical. Additionally, suitable plants must not only tolerate extreme heat but also withstand stagnant water during heavy rainfall. This emphasizes the need for species that balance drought resistance with water resilience to ensure long-term viability.

5.5.3. Practical Alternatives

Many experts identified white walls as a more realistic and cost-effective solution for cooling. While their impact is smaller (up to a 0.75°C reduction compared to the 1.31°C achieved by the combination of green roofs and walls) they require minimal maintenance, are simple to implement, and are broadly applicable to both new and existing buildings. Green roofs and walls were deemed viable primarily in situations where their aesthetic appeal or additional cooling benefits justify the added complexity and costs involved. Scenarios combining green roofs and green walls demonstrated the most significant temperature reductions, reaching 1.31°C by 8am. In contrast, white walls provided smaller but more consistent cooling benefits, with the added advantage of being easier to maintain. However, a small scale research performed in a controlled environment found the minimum temperature difference fully perceptible by humans is 1°C, under which they may perceive a difference but could not be certain of the change (Mizzai, 2023). This implies that the cooling benefits provided by the white wall would go mostly unnoticed, making them inefficient.

5.6. Recommendations for Implementation

In arid environments with limited water resources and older building stock, white-painted walls should be prioritized as a low-maintenance, easy-to-implement alternative for cooling. Green roofs and walls, however, should be targeted for buildings with adequate structural capacity or in high-profile areas where their aesthetic and environmental benefits can justify the added costs. Urban planners should also account for how green roofs and walls interact with the broader cityscape, including neighbouring buildings and street layouts, to optimize their cooling potential and enhance urban microclimates.

5.7. Applicability outside of Riyadh

This research is relevant for other countries with arid climates as it addresses shared challenges such as extreme heat, water scarcity, and urban liveability. By offering a nuanced analysis of cooling strategies, highlighting trade-offs, supporting hybrid solutions and providing a transferable framework for evaluation, this work has the potential to guide urban planners and policymakers worldwide. Using a mix-method approach, this research can be used as a framework for international solutions. This study focuses on orientation-based design, offering a design principle relevant to urban planners in various climates. Furthermore, the scale of this research can easily be increased, allowing for scalability at various levels. The study further illustrates the incremental benefits of combining interventions (e.g. by combining green roofs and walls), allowing other cities to adopt hybrid approaches tailored to their specific conditions. The techniques and scenarios used in this research are not limited to specifically to arid climates, making reproducibility possible as long as local climatic data can be incorporated. From this, it is evident that the methods can easily be generalised and replicated, without being limited to arid climates. The exact results, however, are highly dependent on sun direction and local meteorological data. Nonetheless, the general trends and conclusions drawn from this research — such as the enhanced effectiveness of combining different infrastructure types (e.g., green walls and green roofs), the influence of sun position on the performance of these techniques, and the comparative benefits of reflective coatings versus urban green infrastructure (UGI) — are highly applicable in other arid climates, and could inform future strategies.

5.8. Limitations

The model primarily focuses on air temperature, **omitting humidity**, a crucial factor in assessing thermal comfort. Drought-resistant plants, which tend to absorb humidity, could further exacerbate dryness in arid environments. However, the complex interaction between vegetation and atmospheric moisture was not considered due to the model's limitations and the challenges of simulating such processes. To fully understand these dynamics, advanced modelling techniques would be needed to evaluate how these plants influence surrounding humidity and whether these changes ultimately enhance or diminish thermal comfort. Furthermore, the study focuses on the **limited scale** of a single housing block consisting of eight attached buildings, isolating a specific interaction between the built environment and temperature. While this approach allows for a general analysis, it overlooks broader urban interactions that could influence temperature and airflow dynamics. For example, nearby streets, neighbouring buildings, and the urban canyon effect can significantly impact the cooling performance of green roofs and walls. These factors are essential to understanding the full potential of such interventions, but were beyond the scope of the current model. Additionally, the model did not differentiate between intensive, semi-intensive and extensive roofs and walls, nor did it look at the specifics of the type of plants used on these roofs. Instead, the model used standardize green wall and roof information, pre-set in the software. Also, the model does not investigate how **variation in the material** used for the white-coated building façade, such as cladding systems (such are stone, marble, etc.) or aluminium composite (Abu Dabous et al., 2022), could influence the result. Moreover, simulation results have **not been validated** with field measurements, casting a shadow on the legitimacy of the obtained results.

Key factors such as wind patterns, urban density, and variations in building geometry were not included in the study, despite their critical role in determining the effectiveness of nature-based solutions at a citywide scale. The research assumes an idealized building structure and focuses on a single housing block, thus **creating a simplified** urban context which could be subjected to a lack of accuracy. While this is a common configuration in Riyadh, it limits the robustness of the findings when applied to more diverse urban layouts. Although the interventions provide measurable cooling, their effects are relatively modest, raising questions about their overall impact in extreme heat conditions. For instance, green roofs and walls can reduce temperatures by 1.31°C, which may not be sufficient to significantly alleviate urban heat stress in arid climates. When combined with high maintenance costs and structural challenges, these modest benefits cast doubt on whether such solutions are worth widespread adoption, particularly in resource-constrained regions.

Finally, the model **does not consider the additional ecosystem services** that green roofs and walls might provide, such as improving air quality, enhancing biodiversity, or contributing to urban aesthetics. These benefits could potentially justify their adoption despite the limited cooling effects. Furthermore, the study does not address social acceptance or the willingness of property owners to bear the costs of implementation and maintenance, which are factors that are crucial for the real-world adoption of these interventions.

5.9. Future Work

Future work should address the lack of data for validating ambient air temperature by conducting field measurements over an extended period. This would provide more comprehensive data for comparison. Additionally, results should be assessed on an hourly basis over a full 24-hour cycle, rather than focusing only on three distinct hours, to better capture temperature variations throughout the day.

6

Conclusion

This research investigated the effectiveness of Nature-based Solutions (NbS), particularly green roofs and walls, in cooling dry urban environments. The central question addressed was: To what extent can green roofs and walls be applied to arid regions as robust climate mitigation solutions? To support this, three sub-questions were formulated:

1. What are the (perceived) barriers to and benefits of applying NbS in arid urban environments?
2. What are the methods and scenarios to assess the feasibility of implementing green roofs and walls in arid urban environments?
3. What are the perspectives of pivotal actors, and how can their views be incorporated into the pathways for implementing these solutions?

Through these questions, the study aims to explore the barriers, benefits, and feasibility of these solutions, as well as the perspectives of key stakeholders, to understand how they could be implemented effectively.

This research uses fieldwork, interviews, and remote sensing to develop a comprehensive microclimate model. Remote sensing revealed that Riyadh functions more as an ”urban cool island” than a typical ”urban heat island” with open desert temperatures reaching up to 30°C higher than those in the city. This cooling effect is largely due to the shade provided by buildings and natural elevation, reinforced by the existing vegetation. However, this ”coolness” is relative: by 7 am, urban temperatures already exceeded 27°C, well above thermal comfort levels, indicating the need for further targeted cooling measures.

To address sub-research question 1, interviews were conducted, identifying six critical factors for implementing urban green infrastructure (UGI). These factors were defined as follows: (1) Structural designs must accommodate the weight of vegetation, especially when rain adds additional load. (2) UGI must be resilient to extreme heat and solar radiation. (3) Vegetation should be local, slow-growing, and both drought- and rain-tolerant. (4) Humidity plays a dual role in thermal comfort, as plants both depend on and influence atmospheric humidity. (5) Retrofitting older buildings introduces significant challenges, often requiring documentation and costly structural adaptations. (6) White reflective coatings may be a simpler, more cost-effective alternative to UGI unless the latter provides substantial added benefits.

Building on these results, sub-questions 2 and 3 were addressed by developing a microclimate model to test multiple scenarios at different times of the day. On-site experts were sceptical about the use of UGI, particularly green roofs and walls, arguing that they were neither cost-effective nor climate-adapted, and offering suitable alternatives. These insights were incorporated early in the design process, such as limiting green walls to north-facing orientations to reduce solar exposure. Four scenarios were modelled against a baseline consisting of bare buildings: green roofs, green walls, a combination of green roofs and walls, and white coating. The best cooling results came from the combined green roofs and walls, reducing temperatures by up to 1.31°C. Green walls alone cooled by 1.19°C, and green roofs by 0.88°C. Reflective coatings, while less effective at 0.75°C, were the simplest and most cost-effective solution.

Despite their cooling potential, green roofs and walls face significant challenges, including high maintenance needs, water scarcity, structural issues, and the difficulty of selecting suitable plants for arid climates. Plants that absorb atmospheric humidity may worsen already low humidity levels, reducing thermal comfort. Furthermore, retrofitting older buildings for UGI is complex and costly, making widespread adoption unlikely without clear increased benefits. Reflective coatings emerged as the most practical alternative, offering modest but consistent cooling with minimal maintenance and no structural challenges. While green roofs and walls may provide greater benefits in specific cases, their feasibility in arid regions is limited, particularly when considering their high costs and resource requirements.

While prior research highlights the benefits of green walls and roofs as passive indoor cooling strategies, this study demonstrates that their benefits are limited when used as a robust method to combat the UHI effect. Moreover, it raises important questions about the practicality of NbS in arid environments, cautioning against potential ”greenwashing,” where solutions initially appear sustainable but ultimately prove to be equally as detrimental or worse. The findings suggest that resources might be better allocated to alternative cooling strategies, such as investing in parks, pavements, or traditional native infrastructure, and highlights the need for further research to evaluate how other cooling strategies and parameters compare. Although this research primarily focused on thermal comfort, future studies should investigate additional ecosystem benefits, such as improved air quality, to identify more suitable and sustainable urban interventions. Furthermore, additional work is needed to assess the economic costs of NbS and the policy environment within which they are to be implemented.

7

References

Aboelata, A. (2020). Assessment of green roof benefits on buildings' energy-saving by cooling outdoor spaces in different urban densities in arid cities. *Energy,* 119514. https://doi.org/10.1016/j.energy.2020.119514

Abu Dabous, S., Ibrahim, T., Shareef, S., Mushtaha, E., & Alsyouf, I. (2022). Sustainable façade cladding selection for buildings in hot climates based on thermal performance and energy consumption. Results in Engineering, 16, 100643. https://doi.org/10.1016/j.rineng.2022.100643

Addas, A., & Maghrabi, A. (2020). A Proposed Planning Concept for Public Open Space Provision in Saudi Arabia: A Study of Three Saudi Cities. *International Journal of Environmental Research and Public Health, 17*(16), 5970. https://doi.org.tudelft.idm.oclc.org/10.3390/ijerph17165970

Alaidroos, A., & Krarti, M. (2015). Optimal design of residential building envelope systems in the Kingdom of Saudi Arabia. *Energy and Buildings, 86,* 104-117. https://doi.org/10.1016/j.enbuild.2014.09.083

Albogamy, A., Scott, D., Dawood, N., & Bekr, G. (2013). Addressing crucial risk factors in the Middle East construction industries: a comparative study of Saudi Arabia and Jordan. *In Sustainable Building Conference Coventry University*; West Midlands, UK.

Al-Khawaja, S., & Asfour, O. S. (2024). The impact of COVID-19 on the importance and use of public parks in Saudi Arabia. *Ain Shams Engineering Journal, 15*(1), Article 102286. https://doi.org/10.1016/j.asej.2023.102286

Alattyih, W., Haider H., Boussabaine H. (2020). Risk factors impacting the project value created by green buildings in Saudi Arabia. https://www.mdpi.com/2076-3417/10/21/7388

Almatar, K. M. (2023). Towards sustainable green mobility in the future of Saudi Arabia cities: Implication for reducing carbon emissions and increasing renewable energy capacity. *Heliyon, 9*(3). https://doi.org/10.1016/j.heliyon.2023.e13977

Alqahtany, A. (2022). Green Roofs as an Approach to Enhance Urban Sustainability: A Study of Public Perception in Riyadh, Saudi Arabia. *Buildings.* https://doi.org/10.3390/buildings12122202

Al-Sanea, S., Zedan, M., & Al-Hussain, S. (2013). Effect of masonry material and surface absorptivity on critical thermal mass in insulated building walls. *Applied Energy, 102,* 1063-1070. `https://doi.org/10.1016/J.APENERGY.2012.06.016`

Anderson, V., & Gough, W. (2021). Nature-Based Resilience: A Multi-Type Evaluation of Productive Green Infrastructure in Agricultural Settings in Ontario, Canada. *Atmosphere.* `https://doi.org/10.3390/atmos12091183`

AQICN. (n.d.). Air quality in Riyadh. Retrieved on 4 October 2024 from `https://aqicn.org/city/riyadh/`

Asfour, O. S. (2020). A comparison between the daylighting and energy performance of courtyard and atrium buildings considering the hot climate of Saudi Arabia. *Journal of Building Engineering, 30,* 101299. `https://doi.org/10.1016/j.jobe.2020.101299`

Asadi, I., Shafigh, P., Hassan, Z., & Mahyuddin, N. (2018). Thermal conductivity of concrete – A review. *Journal of Building Engineering.* `https://doi.org/10.1016/J.JOBE.2018.07.002`

Avdan, U., & Jovanovska, G. (2016). Algorithm for Automated Mapping of Land Surface Temperature using LANDSAT 8 Satellite Data. *Journal of Sensors,* Volume 2016, Article ID 1480307, 8 pages. `http://dx.doi.org/10.1155/2016/1480307`

Ayad, A., Fahmy, M., & Kamel, W. (2020). Urban Green and Blue Infrastructure Simulation in a Changing Climate from Microclimate to Energy Consumption: A Case Study in Alexandria, Egypt. `https://doi.org/10.26868/25222708.2019.210676`

Baghaei Daemei, A., Shafiee, E., Chitgar, A. A., & Asadi, S. (2021). Investigating the thermal performance of green wall: Experimental analysis, deep learning model, and simulation studies in a humid climate. *Building and Environment, 205,* 108201. `https://doi.org/10.1016/j.buildenv.2021.108201`

Bigurra-Alzati, C., Ortiz-Gómez, R., Vázquez-Rodríguez, G., López-León, L., & Lizárraga-Mendiola, L. (2020). Water Conservation and Green Infrastructure Adaptations to Reduce Water Scarcity for Residential Areas with Semi-Arid Climate: Mineral de la Reforma, Mexico. *Water.* `https://doi.org/10.3390/w13010045`

Bogis, A., Bork, D., & Miller, P. (2018). Are green infrastructure strategies suitable in arid climates? A design feasibility study from Jeddah city, Saudi Arabia. *International Journal of Architecture and Planning.* `https://doi.org/10.20944/PREPRINTS201809.0013.V1`

Bosch, M., & Sang, Å. (2017). Urban natural environments as nature-based solutions for improved public health – A systematic review of reviews. *Environmental Research, 158,* 373-384. `https://doi.org/10.1016/J.ENVRES.2017.05.040`

Catalano, C., Meslec, M., Boileau, J., Guarino, R., Aurich, I., Baumann, N., Chartier, F., Dalix, P., Deramond, S., Laube, P., Lee, A., Ochsner, P., Pasturel, M., Soret, M., & Moulherat, S. (2021). Smart Sustainable Cities of the New Millennium: Towards Design for Nature. *Circular Economy and Sustainability, 1,* 1053-1086. `https://doi.org/10.1007/s43615-021-00100-6`

Chang, Hsueh-Sheng, Zih-Hong Lin, & Yi-Ya Hsu. (2021). Planning for green infrastructure and mapping synergies and trade-offs: A case study in the Yanshuei River Basin, Taiwan. *Urban Forestry &*

Urban Greening, 65, 127325. https://doi.org/10.1016/j.ufug.2021.127325

Cheung, P., Livesley, S., & Nice, K. (2021). Estimating the cooling potential of irrigating green spaces in 100 global cities with arid, temperate, or continental climates. *Sustainable Cities and Society, 71,* 102974. https://doi.org/10.1016/J.SCS.2021.102974

Chow, M. F., & Bakar, M. F. A. (2018). Environmental Benefits of Green Roof to the Sustainable Urban Development: A Review. *Proceedings of the 1st Global Civil Engineering Conference—GCEC17, Kuala Lumpur, Malaysia, 25–28 July 2017;* Universiti Tenaga Nasional: Selangor, Malaysia, 2018; pp. 1525–1541.

Clark, C., Talbot, B., Bulkley, J., & Adiaens, P. (2005). Optimization of green roofs for air pollution mitigation. *Proceedings of the 3rd North American Green Roof Conference: Greening Rooftops for Sustainable Communities, Washington, DC, USA, 4–6 May 2005;* pp. 482–597.

Coma, J., Pérez, G., & Cabeza, L. F. (2018). Green roofs to enhance the thermal performance of buildings and outdoor comfort. *Nature Based Strategies for Urban and Building Sustainability;* Butterworth-Heinemann. https://doi.org/10.1016/B978-0-12-812150-4.00010-0

Davies, C., & Lafortezza, R. (2019). Transitional path to the adoption of nature-based solutions. *Land Use Policy.* https://doi.org/10.1016/J.LANDUSEPOL.2018.09.020

Diakaki, C., Grigoroudis, E., & Kolokotsa, D. (2008). Towards a multi-objective optimization approach for improving energy efficiency in buildings. *Energy and Buildings, 40,* 1747-1754. https://doi.org/10.1016/j.enbuild.2008.03.002

Dorst, H., Jagt, A., Raven, R., & Runhaar, H. (2019). Urban greening through nature-based solutions – Key characteristics of an emerging concept. *Sustainable Cities and Society.* https://doi.org/10.1016/J.SCS.2019.101620

Duffin, R., & Knowles, G. (1984). A passive wall design to minimize building temperature swings. *Solar Energy, 33,* 337-342. https://doi.org/10.1016/0038-092X(84)90163-4

El-Awady, S., Al-Mushayqih, S., & Al-Oudah, E. (2020). An analytical study of the determinants of foreign investment in Saudi Arabia “Saudi Vision 2030.” *The Business and Management Review, 11*(01). https://doi.org/10.24052/bmr/v11nu01/art-02

El-Gayar, S., Gad, H., & Gad, H. (2014). Absorptance of different local coated surfaces to solar radiation in Egypt. *Misr Journal of Agricultural Engineering, 31,* 1563-1576. https://doi.org/10.21608/mjae.2014.98417

Explained by Dom (2023). Dubai’s Economy Is In Deep Trouble - Here’s Why. YouTube. Retrieved November 14, 2023, from https://www.youtube.com/watch?v=JlJeM-feeh8&ab_channel=ExplainedwithDom

Farag, A. A. (2019). The Story of NEOM City: Opportunities and Challenges. In Attia, S., Shafik, Z., & Ibrahim, A. (Eds.), *New Cities and Community Extensions in Egypt and the Middle East.* Springer, Cham. https://doi.org/10.1007/978-3-319-77875-4_3

Flyvbjerg, B. (2017). Introduction: The Iron Law of Megaproject Management. *The Oxford Handbook of Megaproject Management,* Oxford University Press, Chapter 1, pp. 1-18. https://ssrn.com/abstract=2742088

Frantzeskaki, N., McPhearson, T., Collier, M., Kendal, D., Bulkeley, H., Dumitru, A., Walsh, C., Noble, K., Van Wyk, E., Ordóñez, C., Oke, C., & Pintér, L. (2019). Nature-Based Solutions for Urban Climate Change Adaptation: Linking Science, Policy, and Practice Communities for Evidence-Based Decision-Making. *BioScience.* https://doi.org/10.1093/BIOSCI/BIZ042

Gavrilidis, A., Popa, A., Niță, M., Onose, D., & Badiu, D. (2020). Planning the "unknown": Perception of urban green infrastructure concept in Romania. *Urban Forestry & Urban Greening, 51,* 126649. https://doi.org/10.1016/j.ufug.2020.126649

Gerrand, N. (2023, June 20). Megaprojects: Two reasons why they go wrong (and four key ingredients for success). *Construction Briefing.* Retrieve on December 26, 2024, fromhttps://www.constructionbriefing.com/news/megaprojects-two-reasons-why-they-go-wrong-and-four-key-ingredients-for-success-/8028979.article

Gunawardena, K., Wells, M., & Kershaw, T. (2017). Utilizing green and bluespace to mitigate urban heat island intensity. *The Science of the Total Environment, 584-585,* 1040-1055. https://doi.org/10.1016/j.scitotenv.2017.01.158

Ibtissam, B., Salima, L., & Benoudjafer, I. (2022). Techno-Economic Analysis and Cost Benefits of Green Walls for Building in Extreme Climate: Case Study Southwest of Algeria. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, Volume 94*(1), 108-119. https://doi.org/10.37934/arfmts.94.1.108119

Imam, A. (2023). Examining the impact of Green Riyadh Project on alleviating urban heat island effects. *Journal of Umm Al-Qura University for Engineering and Architecture, 14,* 201-211. https://doi.org/10.1007/s43995-023-00030-4

International Organization for Standardization. (2006). ISO 14040:2006 - Environmental management - Life cycle assessment - Principles and framework.

Andric, I., Kamal, A. & Al-Ghamdi, S.G. (2020). Efficiency of green roofs and green walls as climate change mitigation measures in extremely hot and dry climate: Case study of Qatar. *Energy Reports, 6,* 2476-2489. https://doi.org/10.1016/j.egyr.2020.09.006

Jamali, F.S., Khaledi, S., & Razavian, M.T. (2021). Priority Areas for Developing Green Infrastructure in Semi-arid Cities: A Case Study of Tehran. *Environment and Urbanization Asia, 12,* 118-135. https://doi.org/10.1177/0975425321990326

Khabaz, A. (2018). Construction and design requirements of green buildings' roofs in Saudi Arabia depending on thermal conductivity principle. *Construction and Building Materials, 186,* 1119–1131. https://doi.org/10.1016/j.conbuildmat.2018.07.234

Klingmann, A. (2022). Rescripting Riyadh: How the capital of Saudi Arabia employs urban megaprojects as catalysts to enhance the quality of life within the city's neighborhoods. *Journal of Place Management and Development, 16*(1), 45–72. https://doi.org/10.1108/jpmd-06-2021-0062

Koc, C.B., Osmond, P., & Peters, A. (2018). Evaluating the cooling effects of green infrastructure: A systematic review of methods, indicators, and data sources. *Solar Energy, 166,* 486-508. https://doi.org/10.1016/J.SOLENER.2018.03.008

Kraemer, R., & Kabisch, N. (2022). Parks Under Stress: Air Temperature Regulation of Urban Green Spaces Under Conditions of Drought and Summer Heat. *Frontiers in Environmental Sciences*. Volume 10 - 2022.https://doi.org/10.3389/fenvs.2022.849965

Kwan, M., & Knigge, L. (2006). Doing Qualitative Research Using GIS: An Oxymoronic Endeavor? *Environment and Planning A, 38,* 1999-2002. https://doi.org/10.1068/a38462

Kingma, B., Frijns, A., & van Marken Lichtenbelt, W. (2012). The thermoneutral zone: implications for metabolic studies. *Frontiers in Bioscience (Elite edition), 4*(5), 1975–1985. https://doi-org.tudelft.idm.oclc.org/10.2741/e518

Li, Y., Xie, Y., Syu, J., Huang, C., Tsai, H., Cheng, T., Chen, Y., & Lee, W. (2021). A Study on the Influence of the Next Generation Colored Inorganic Geopolymer Material Paint on the Insulation Measurement of Concrete Building Shell. *Sustainability.* https://doi.org/10.3390/su14010164

Loo, S. C., Abdul-Rahman, H., & Wang, C. (2013). Managing External Risks for International Architectural, Engineering, and Construction (AEC) Firms Operating in Gulf Cooperation Council (GCC) States. *Project Management Journal, 44*(5), 70-88. https://doi.org/10.1002/pmj.21365

Mahmoud, A., Asif, M., Hassanain, M., Babsail, M., & Sanni-Anibire, M. (2017). Energy and Economic Evaluation of Green Roofs for Residential Buildings in Hot-Humid Climates. *Buildings, 7,* 30. https://doi.org/10.3390/BUILDINGS7020030

Mahmoud, I., & Morello, E. (2021). Co-creation Pathway for Urban Nature-Based Solutions: Testing a Shared-Governance Approach in Three Cities and Nine Action Labs. *Smart and Sustainable Planning for Cities and Regions.* pp 259–276. https://doi.org/10.1007/978-3-030-57764-3_17

Mazzai, A. (2023, July 5). *Yes, you can feel one degree.* Foresight – The CMCC Observatory on Climate Policies and Futures. Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici. Retrieved December 26, 2024, from https://www.climateforesight.eu/interview/yes-you-can-feel-one-degree/

Mirzoev, T. N., Zhu, L., Yang, Y., Zhang, T., Roos, E., Pescatori, A., & Matsumoto, A. (2020). The Future of Oil and Fiscal Sustainability in the GCC Region. United Nations. https://www.imf.org/en/Publications/Departmental-Papers-Policy-Papers/Issues/2020/01/31/The-Future-of-Oil-and-Fiscal-Sustainability-in-the-GCC-Region-48934

Mukherjee, P. (1992). Properties of High-Density Concrete. *Journal of Testing and Evaluation, 20,* 78-86. https://doi.org/10.1520/JTE11901J

Nahiduzzaman, K., Aldosary, A. S., & Rahman, M. T. (2015). Flood induced vulnerability in strategic plan making process of Riyadh city. *Habitat International, 49,* 375-385. https://doi.org/10.1016/j.habitatint.2015.05.034

National Center for Environmental Compliance. (n.d.). National Center for Environmental Compliance - Kingdom of Saudi Arabia. Retrieved November 14 2023, from https://www.my.gov.sa/wps/portal

/snp/agencies/agencyDetails/AC466/

Nejat, P. (2018). Windcatcher as a Persian Sustainable Solution for Passive Cooling. *Civil Engineering Research Journal.* https://doi.org/10.19080/cerj.2018.06.555679

Perini, K., & Rosasco, P. (2016). Is greening the building envelope economically sustainable? An analysis to evaluate the advantages of economy of scope of vertical greening systems and green roofs. *Urban Forestry & Urban Greening, 20,* 328-337. https://doi.org/10.1016/j.ufug.2016.08.002

Priyadarsini, R., & Wong, N. (2005). Building Surfaces and their Effect on the Urban Thermal Environment. *Architectural Science Review*, 48, 345 - 356. https://doi.org/10.3763/asre.2005.4842

Qin, X., Wu, X., Chiew, Y. M., & Li, Y. (2012). A green roof test bed for stormwater management and reduction of urban heat island effect in Singapore. *British Journal of Environment and Climate Change*, 2(4), 410. https://doi.org/10.9734/BJECC/2012/2704

Projects. Saudi Vision 2030. (n.d.). Retrieved November 14, 2023, from https://www.vision2030.gov.sa/en/projects/

Raji, B., Tenpierik, M. J., & van den Dobbelsteen, A. (2015). The impact of greening systems on building energy performance: A literature review. *Renewable and Sustainable Energy Reviews, 45,* 610-623. https://doi.org/10.1016/j.rser.2015.02.011

Razzaghmanesh, M., & Razzaghmanesh, M. (2017). Thermal performance investigation of a living wall in a dry climate of Australia. *Building and Environment, 112,* 45-62. https://doi.org/10.1016/J.BUILDENV.2016.11.023

Raymond, C., Frantzeskaki, N., Kabisch, N., Berry, P., Breil, M., Ni□ă, M., Geneletti, D., & Calfapietra, C. (2017). A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environmental Science & Policy, 77,* 15-24. https://doi.org/10.1016/J.ENVSCI.2017.07.008

Reu Junqueira, J., Serrao-Neumann, S., & White, I. (2021). Managing urban climate change risks: Prospects for using green infrastructure to increase urban resilience to floods. In T. M. Letcher (Ed.), *The Impacts of Climate Change* (pp. 379-396). Elsevier. https://doi.org/10.1016/B978-0-12-822373-4.00013-6

Rosso, F., Pisello, A., Castaldo, V., Fabiani, C., Cotana, F., Ferrero, M., & Jin, W. (2017). New cool concrete for building envelopes and urban paving: Optics-energy and thermal assessment in dynamic conditions. *Energy and Buildings, 151,* 381-392. https://doi.org/10.1016/J.ENBUILD.2017.06.051

Royal Commission for Riyadh City. (2020). *Ariyadh Plants: Plant Guide for Riyadh.* Riyadh: Royal Commission for Riyadh City. ISBN: 978-603-90582-1-2.

Riyadh Green. (n.d.). Overview. *Riyadh Green.* Retrieved November 14, 2023, from https://riyadhgreen.sa/en/

Paolini, R., Zani, A., Poli, T., Antretter, F., & Zinzi, M. (2017). Natural aging of cool walls: Impact on solar reflectance, sensitivity to thermal shocks and building energy needs. *Energy and Buildings, 153,* 287-296. https://doi.org/10.1016/J.ENBUILD.2017.08.017

Sarabi, S., Han, Q., Georges, A., Romme, L., Vries, B., & Wendling, L. (2019). Key Enablers of and Barriers to the Uptake and Implementation of Nature-Based Solutions in Urban Settings: A Review. *Resources, 8(3),* 121 https://doi.org/10.3390/RESOURCES8030121

Sahnoune, S., & Benhassine, N. (2017). Quantifying the Impact of Green-Roofs on Urban Heat Island Mitigation. *International Journal of Environmental Science and Development, 8,* 116-123. https://doi.org/10.18178/ijesd.2017.8.2.932

Seyam, S. (2019). The impact of greenery systems on building energy: Systematic review. *Journal of Building Engineering, 26,* 100887. https://doi.org/10.1016/j.jobe.2019.100887

Sepielak, K., Wladyka, D., & Yaworsky, W. (2019). Unsung interpreters: the jumbled practice of language translation in contemporary field research – a study of anthropological field sites in the Arab League countries. *Language and Intercultural Communication, 19,* 421-437. https://doi.org/10.1080/14708477.2019.1585443

Statista. (n.d.). Monthly maximum temperatures in Riyadh, Saudi Arabia from January to December. Retrieved October 6, 2024, from https://www.statista.com/statistics/619431/saudi-arabia-riyadh-monthly-maximum-temperatures/

Sposito, C., & Scalisi, F. (2023). Reflections and trajectories for interdisciplinary research on the ecological transition. *AGATHÓN | International Journal of Architecture, Art and Design, 13,* 3–18. https://doi.org/10.19229/2464-9309/1302023

Sultan, B., Katar, I. M., & Al-Atroush, M. E. (2021). Towards sustainable pedestrian mobility in Riyadh city, Saudi Arabia: A case study. *Sustainable Cities and Society, 69,* 102831. https://doi.org/10.1016/j.scs.2021.102831

Sun, Z., Zhang, Z., & Duan, C. (2015). The applicability of the wall implanted with heat pipes in winter of China. *Energy and Buildings, 104,* 36-46. https://doi.org/10.1016/J.ENBUILD.2015.06.082

Taghavi-Jeloudar, M., Han, M., Davoudi, M., & Kim, M. (2013). Review of Ancient Wisdom of Qanat, and Suggestions for Future Water Management. *Environmental Engineering Research, 18,* 57-63. https://doi.org/10.4491/EER.2013.18.2.057

The trouble with megaprojects. GIS Reports. (2023, July 11). Retrieved on November 14, 2023, from https://www.gisreportsonline.com/r/trouble-megaprojects/

United Nations, Department of Economic and Social Affairs. (2018). The 2018 revision of world urbanization prospects. Retrieved from https://www.un.org/en/desa/2018-revision-world-urbanization-prospects

University of Arizona. (2012). Thermal comfort and heat balance. Retrieved on September 15, 2024, from http://www.atmo.arizona.edu/students/courselinks/fall12/atmo336/lectures/sec1/comfort.html#:~:text=The%20ideal%20conditions%20for%20a,easily%20maintain%20its%20core%20temperature.

Valambhiya, H., Tuvar, T., & Rayjada, P. (2017). History and case study on light transmitting concrete. *International Journal of Emerging Technologies and Innovative Research (www.jetir.org), ISSN:2349-5162, Vol.4, Issue 1*, page no.22-31, Available :http://www.jetir.org/papers/JETIR1701004.pdf

van der Laarsen, G. (2023). Towards climate just nature-based solutions: A social vulnerability framework for mapping ecosystem service demand (thesis). *Delft University of Technology, Delft.*

van Renterghem, T. (2018). Green roofs for acoustic insulation and noise reduction. *Nature Based Strategies for Urban and Building Sustainability;* Butterworth-Heinemann: Oxford, UK; Chapter 3.8; pp. 167–179. `https://doi.org/10.1016/B978-0-12-812150-4.00016-1`

Wahl, E. (2017). Buildings in Arid Desert Climate: Improving Energy Efficiency with Measures on the Building Envelope (Dissertation). Retrieved from `https://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-62703`

What is urban regeneration? Definition and types. Enel X. (n.d.). Retrieved on September 15, 2024, from `https://corporate.enelx.com/en/question-and-answers/what-is-urban-regeneration`

WeatherSpark. (2023). Historical weather during 2023 in Riyadh, Saudi Arabia. Retrieved on 4 October, 2024, from `https://weatherspark.com/h/y/104018/2023/Historical-Weather-during-2023-in-Riyadh-Saudi-Arabia`

Weather Underground. (2023, August 2). Riyadh historical weather. Retrieved on 4 October, 2024 from `https://www.wunderground.com/history/daily/OERK/date/2023-8-2`

Wickenberg, B., McCormick, K., & Olsson, J. (2021). Advancing the implementation of nature-based solutions in cities: A review of frameworks. *Environmental Science & Policy.* `https://doi.org/10.1016/j.envsci.2021.08.016`

Wikipedia. (n.d.). Riyadh. In Wikipedia, The Free Encyclopedia. Retrieved June 20, 2024, from `https://en.wikipedia.org/wiki/Riyadh`

Wong, N. H., Tay, S. F., Wong, R., Ong, C. L., & Sia, A. (2003). Life cycle cost analysis of rooftop gardens in Singapore. *Building and Environment, 38,* 499–509. `https://doi.org/10.1016/S0360-1323(02)00131-2`

Yang, J., & Wang, Z. (2017). Planning for a sustainable desert city: The potential water buffering capacity of urban green infrastructure. *Landscape and Urban Planning, 167,* 339-347. `https://doi.org/10.1016/J.LANDURBPLAN.2017.07.014`

Yang, W., Wong, N.H., & Jusuf, S. (2013). Thermal comfort in outdoor urban spaces in Singapore. *Building and Environment, 59,* 426-435. `https://doi.org/10.1016/J.BUILDENV.2012.09.008`

A

Ethical Guidelines and Risk Management

In line with university ethical guidelines, the research carefully considered participant safety and data privacy. While no formal risk-planning session was held to identify and mitigate potential risks before starting the study, the planning below shows that the privacy of the participants was carefully considered. The following steps were taken to adhere to ethical standards:

- Risk Assessment: A thorough risk assessment was conducted, covering key areas like Participants, Location, Partners, and Data & Privacy.
  - Participants: Identities were kept anonymous to ensure no risks to interviewees.
  - Location: Interview settings were chosen to be safe and comfortable.
  - Data & Privacy: Strict data protection measures were implemented, following university policies and international ethical standards.
- Informed Consent: Participants were fully briefed on the study's goals and their rights, including the right to withdraw at any time. They received a formal consent document covering research participation and data privacy.
- Mitigation Measures: Steps were taken to minimize risks, such as:
  - Securely recording interviews with access limited to authorized researchers.
  - Data were anonymized before analysis to protect participant identities.

Managing Risks: A Data Management Plan was submitted to the university's ethics committee, detailing data storage, processing, and deletion methods. The research followed the 1964 Helsinki Declaration to ensure the protection of human subjects.

The data management plan, along with the completed human research ethics checklist and informed consent materials, was submitted to the Human Research Ethics Committee (HREC) for review. Approval was subsequently granted by the committee.

B

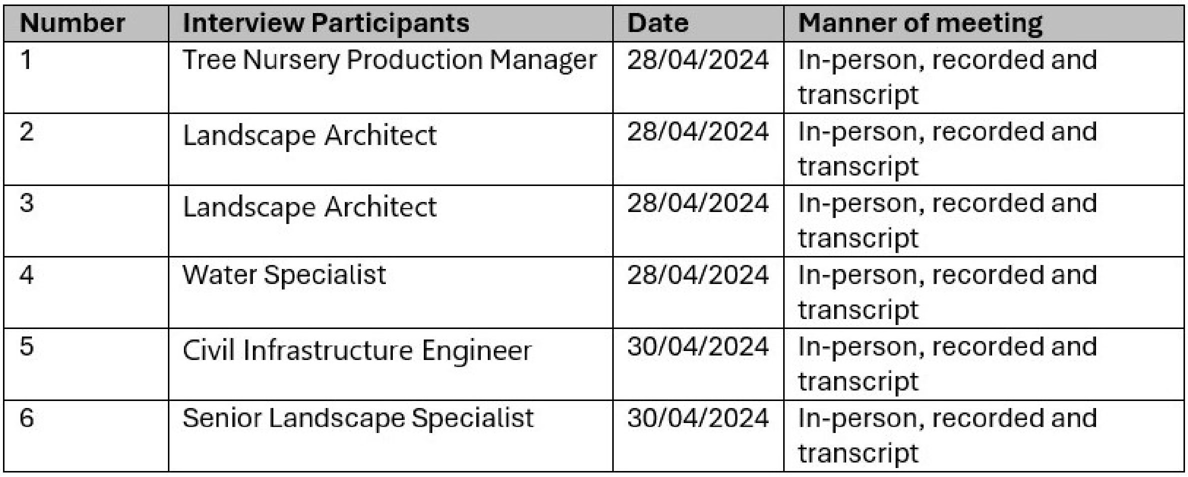
Interview Questions

1. What are the contributing factors to the decline in vegetation areas in arid urban environments, and how can green infrastructure be adapted to avoid further desiccation?
   Goal: This question aims to identify the root causes behind the loss of vegetation in arid cities like Riyadh and explore adaptive strategies for preventing further ecological degradation through green infrastructure. *Answered by interviewee(s): A*
2. What are the potential benefits and drawbacks of integrating green roofs and walls into Riyadh's urban infrastructure?
   Goal: This question seeks to assess the advantages and challenges of implementing green roofs and walls, considering Riyadh's unique climate and urban needs. *Answered by interviewee(s): A, B, C, D*
3. Can you discuss any innovative practices or technologies that could support the development of green infrastructure in Riyadh?
   Goal: The aim here is to explore cutting-edge technologies and methods that could aid the successful implementation and sustainability of green infrastructure in the city. *Answered by interviewee(s): A, B, C, D*
4. Which local plant species are most suitable for green roofs and walls in Riyadh? And why?
   Goal: This question focuses on identifying plant species that can thrive in Riyadh's climate, ensuring that green roofs and walls are both functional and sustainable. *Answered by interviewee(s): A*
5. What are the substrate and nursery requirements for these plants?
   Goal: This question seeks to determine the ideal growing conditions, such as soil types and plant care, necessary for cultivating vegetation on green roofs and walls. *Answered by interviewee(s): A*
6. How can green roofs and walls be designed to thrive in Riyadh's arid climate?
   Goal: The objective is to identify the best design practices that allow green infrastructure to withstand and thrive in the city's harsh, dry environment. *Answered by interviewee(s): B, C, D*
7. How can vegetation on green roofs and walls impact the UHI effect in Riyadh?
   Goal: This question aims to explore the role of green infrastructure in mitigating the Urban Heat Island (UHI) effect, which is a major concern in Riyadh's hot climate. *Answered by interviewee(s): B, C*
8. To your knowledge, has the relation between impact and green roofs been studied and what are the conclusions?
   Goal: This seeks to gather insights on existing research regarding the effectiveness of green roofs in addressing urban heat and other environmental impacts. *Answered by interviewee(s): B, C*

9. What design considerations need to be taken into account to maximize the cooling benefits?
   Goal: The purpose of this question is to determine the key design factors that maximize the cooling potential of green roofs and walls. *Answered by interviewee(s): B, C*
10. What irrigation systems are best suited for sustaining green roofs and walls in Riyadh?
    Goal: This question aims to identify the most effective irrigation methods to support plant life on green roofs and walls in an arid city like Riyadh. *Answered by interviewee(s): D*
11. Could you elaborate on the quality, quantity and sources of water required for these systems?
    Goal: This question seeks detailed information on the water needs of green infrastructure, including how to source and manage water in a sustainable way. *Answered by interviewee(s): D*
12. How effective are green roofs and walls in mitigating flood risks in urban environments like Riyadh?
    Goal: The goal is to explore the potential of green roofs and walls to reduce flood risks by enhancing stormwater management in an urban setting. *Answered by interviewee(s): D, E*
13. How could green roofs be specifically designed to support an effective urban storm management system?
    Goal: This question focuses on how green roofs can be integrated into Riyadh's stormwater management strategies to mitigate flooding. *Answered by interviewee(s): D, E*
14. From an urban planning perspective, what changes are needed to facilitate the incorporation of green roofs and walls in Riyadh?
    Goal: The aim is to identify the necessary urban planning adjustments to accommodate and promote green infrastructure within the city. *Answered by interviewee(s): F*
15. How do green roofs and walls fit into the broader plan for urban development in line with Saudi Vision 2030?
    Goal: This question seeks to understand how green infrastructure aligns with the long-term urban and environmental goals outlined in Saudi Vision 2030. *Answered by interviewee(s): F*
16. Why is there an interest for new designs rather than region-specific traditional infrastructure?
    Goal: This question aims to uncover why modern design approaches are being favoured over traditional infrastructure in the context of green development in Riyadh. *Answered by interviewee(s): F*

C

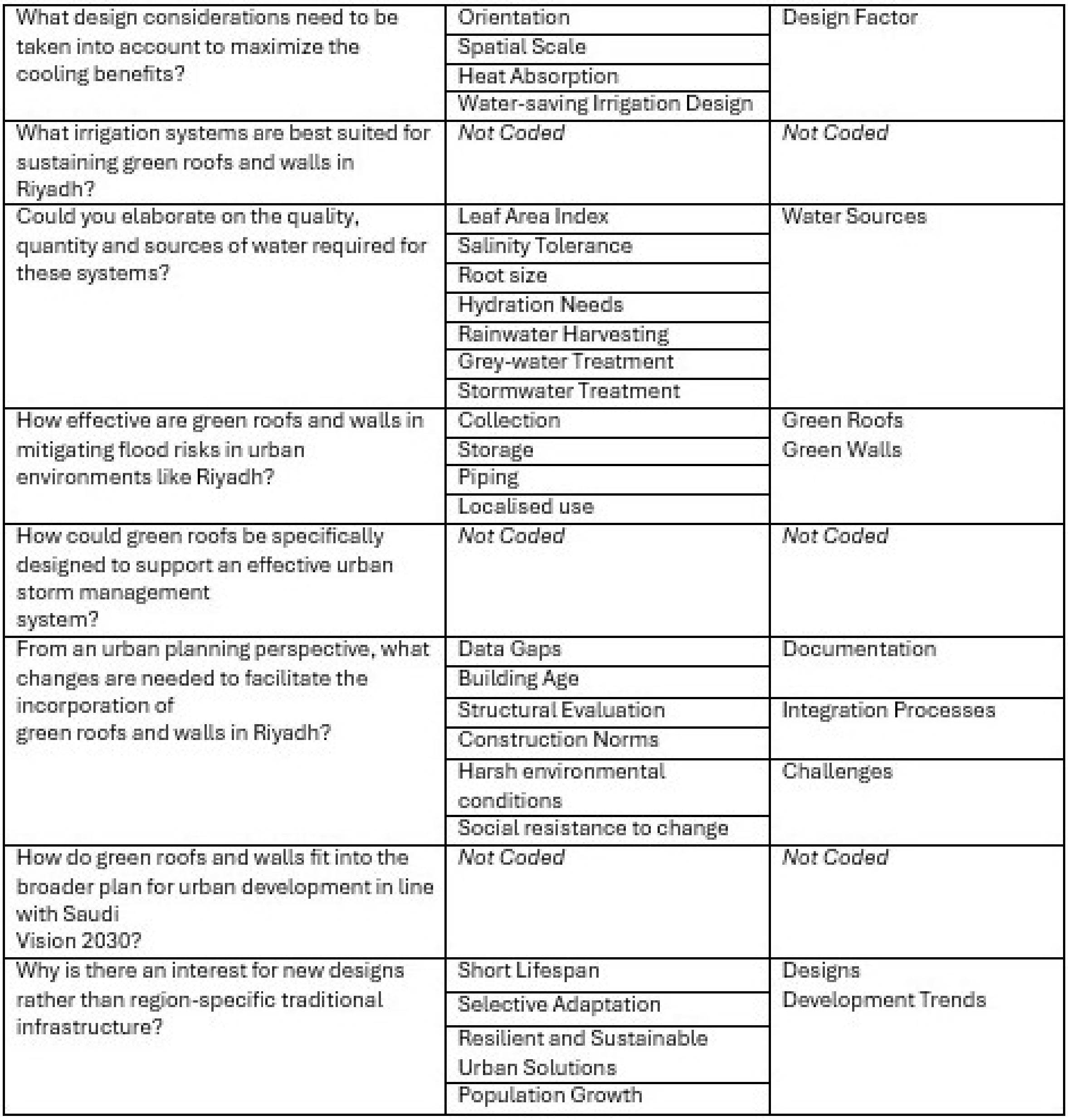
Interview Participant & Coding



Number	Interview Participants	Date	Manner of meeting
1	Tree Nursery Production Manager	28/04/2024	In-person, recorded and transcript
2	Landscape Architect	28/04/2024	In-person, recorded and transcript
3	Landscape Architect	28/04/2024	In-person, recorded and transcript
4	Water Specialist	28/04/2024	In-person, recorded and transcript
5	Civil Infrastructure Engineer	30/04/2024	In-person, recorded and transcript
6	Senior Landscape Specialist	30/04/2024	In-person, recorded and transcript

Figure C.1: Brief information overview of the interviewed participants.

Question	**Open Coding**	**Axial Coding**
What are the contributing factors to the decline in vegetation areas in arid urban environments, and how can green infrastructure be adapted to avoid further desiccation?	Urban Growth	Urbanisations
	Water Needs	
What are the potential benefits and drawbacks of integrating green roofs and walls into Riyadh's urban infrastructure?	Improved micro-climate	Structural Limitations & Benefits Aesthetic Concerns
	Shading effect	
	Urban Greening and Sustainability	
	High implementation costs	
	Load challenges for existing buildings	
	Thermal Insulation	
Can you discuss any innovative practices or technologies that could support the development of green infrastructure in Riyadh?	Urban Agriculture	Innovation
	Adaptative	Sustainability
	Native Species	
	Exotic Species	
	Nursery	
	Certification	
	International Standards	
	Key Performance Indicators	Performance
	Water holding	
	Hydroponic Systems	
How can green roofs and walls be designed to thrive in Riyadh's arid climate?	Heat-resistant Species	Resilience.
	Low Water-demand Species	
	Drought-tolerant Species	
	Low salinity tolerance	
	Heat Accumulation	
	Reflective Materials	
	Irrigation	
	Resource-efficiency	Cost-Benefit Analysis
	Cost-effectiveness	
What are the substrate and nursery requirements for these plants?	Local	Vegetative practices
	Composition	
	International standards	
	Compliance	
	Infrastructure	
Which local plant species are most suitable for green roofs and walls in Riyadh? And why?	Aromatic Herbs	Vegetation Resilience
	Slow-growing Species	
	Low maintenance	
	Suitability	
How can vegetation on green roofs and walls impact the UHI effect in Riyadh?	*Not Coded*	*Not Coded*
To your knowledge, has the relation between impact and green roofs been studied and what are the conclusions?	Lack of context-specific studies	Existing research
	Phoenix, Arizona	
	China	



What design considerations need to be taken into account to maximize the cooling benefits?	Orientation Spatial Scale Heat Absorption Water-saving Irrigation Design	Design Factor
What irrigation systems are best suited for sustaining green roofs and walls in Riyadh?	*Not Coded*	*Not Coded*
Could you elaborate on the quality, quantity and sources of water required for these systems?	Leaf Area Index Salinity Tolerance Root size Hydration Needs Rainwater Harvesting Grey-water Treatment Stormwater Treatment	Water Sources
How effective are green roofs and walls in mitigating flood risks in urban environments like Riyadh?	Collection Storage Piping Localised use	Green Roofs Green Walls
How could green roofs be specifically designed to support an effective urban storm management system?	*Not Coded*	*Not Coded*
From an urban planning perspective, what changes are needed to facilitate the incorporation of green roofs and walls in Riyadh?	Data Gaps Building Age	Documentation
	Structural Evaluation Construction Norms	Integration Processes
	Harsh environmental conditions Social resistance to change	Challenges
How do green roofs and walls fit into the broader plan for urban development in line with Saudi Vision 2030?	*Not Coded*	*Not Coded*
Why is there an interest for new designs rather than region-specific traditional infrastructure?	Short Lifespan Selective Adaptation Resilient and Sustainable Urban Solutions Population Growth	Designs Development Trends

Figure C.2: Overview of the interview questions divided by their open and axial codes.

D

Data Acquisition Remote Sensing

	East Riyadh	West Riyadh
File	LC08_L1TP_165043_20230818_20230825_02_T1	LC08_L1TP_166043_20230825_20230905_02_T1
Bands	_B4; _B5; _B10	_B4; _B5; _B10
Date Measurement	18/08/2023	25/08/2023
Time Measurement	07:00	07:00
Date Acquired	August 19th 2024	August 19th 2024
Website	https://earthexplorer.usgs.gov	https://earthexplorer.usgs.gov

Table D.1: Landsat 8 Imagery Data for East and West Riyadh

E

Measurements for the input values of the model

The ENVI-met model layout is initially designed in 2.5D before being rendered into a 3D digital environment by the software. Building and street dimensions are determined using measurements taken from Google Earth. To establish the average street dimensions, ten vertical and ten horizontal street lengths are randomly measured, and their averages are calculated. These averages are applied to the streets surrounding the building in the model. One building consists of 8 housing blocks. For building dimensions, ten complexes, each containing eight units in line with Riyadh's urban planning, are selected. The length and width of each block are measured, and their averages are calculated. Additionally, 20 individual housing units (cubes) from the selected blocks are measured for width and length, and an overall average is determined.

Averages	Measured (in m)	Model Input Value (in m)
Length	98.77	100
Width	49.44	50
Cube L	21.7805	25
Cube W	21.338	25
St. Horiz	17.166	20
St. Verti	14.889	15

Table E.1: Comparison of measured values and model input values. W: Width; L: Length

To simplify the modelling, the averages were rounded to the nearest multiple of 5. The average size of a cube is 21.78m by 21.35m, while the average size of a block, consisting of 4 cubes in length and 2 cubes in width, is 98.77m by 49.44m. For consistency, cubes were rounded up to 25m by 25m, disregarding narrow corridors between houses within certain blocks, as these scenarios are excluded from the model. Similarly, the width of horizontal streets was rounded up from 17.1m to 20m, rather than down to 15m, to reflect observations that horizontal streets are typically wider than adjacent vertical streets, which were also rounded up to 15m. The selection of 10 buildings and the units within them for measurements was mostly random but with intentional exclusions. Certain building complexes or units were omitted if they appeared to deviate from the broader urban planning pattern of the district, as observed in Google Earth. Excluded cases include complexes with only six units, often located at the district's edges, or housing units with large adjacent corridors. Measurements were taken using Google Earth rather than ArcGIS, as its satellite images offered greater clarity. However, these measurements lacked precise accuracy, relying on visual estimation to determine the start and end points of complexes and units. Despite this limitation, the recorded values were found to be consistent across the dataset.

Streets	Index	Value
Horizontal	1	16.53
	2	15.36
	3	15.30
	4	17.95
	5	18.22
	6	18.35
	7	17.21
	8	18.25
	9	18.74
	10	15.75
Vertical	1	15.10
	2	15.47
	3	15.19
	4	14.28
	5	11.22
	6	15.72
	7	14.48
	8	14.32
	9	18.13
	10	14.98

Table E.2: Values for Streets Horizontal and Streets Vertical.

Measurements	Attribute	Value (m)
Building 1	Length	98.7
	Width	54.45
	Cube L	23.59
	Cube W	22.49
Building 2	Length	99.68
	Width	51.84
	Cube 1 L	21.46
	Cube 1 W	20.45
	Cube 2 L	20.2
	Cube 2 W	20.31
	Cube 3 L	20.31
	Cube 3 W	19.79
Building 3	Length	103.37
	Width	52.95
	Cube L	19.34
	Cube W	19.58
Building 4	Length	98.06
	Width	45.22
	Cube 1 L	22.59
	Cube 1 W	22.38
	Cube 2 L	22.31
	Cube 2 W	25.3
Building 5	Length	99.28
	Width	45.95
	Cube 1 L	24.8
	Cube 1 W	22.98
	Cube 2 L	23.13
	Cube 2 W	23.5
Building 6	Length	102.7
	Width	50.5
	Cube L	24.96
	Cube W	23.69
Building 7	Length	96.9
	Width	52.24
	Cube 1 L	20.69
	Cube 1 W	20.86
	Cube 2 L	20.26
	Cube 2 W	17.89
Building 8	Length	92.86
	Width	44.83
	Cube 1 L	20.25
	Cube 1 W	19.94
	Cube 2 L	20.25
	Cube 2 W	18.26
	Cube 3 L	22.89
	Cube 3 W	22.17
	Cube 4 L	20
	Cube 4 W	19.93
Building 9	Length	94.99
	Width	43.14
	Cube 1 L	20.08
	Cube 1 W	21.24
	Cube 2 L	21.78
	Cube 2 W	19.7
Building 10	Length	101.16
	Width	53.28
	Cube 1 L	22.44
	Cube 1 W	25.72
	Cube 2 L	24.28
	Cube 2 W	20.58

Table E.3: Measurements of buildings and their respective attributes. W: Width; L: Length

F

Land Surface Temperature Overlaid with Gray Scale

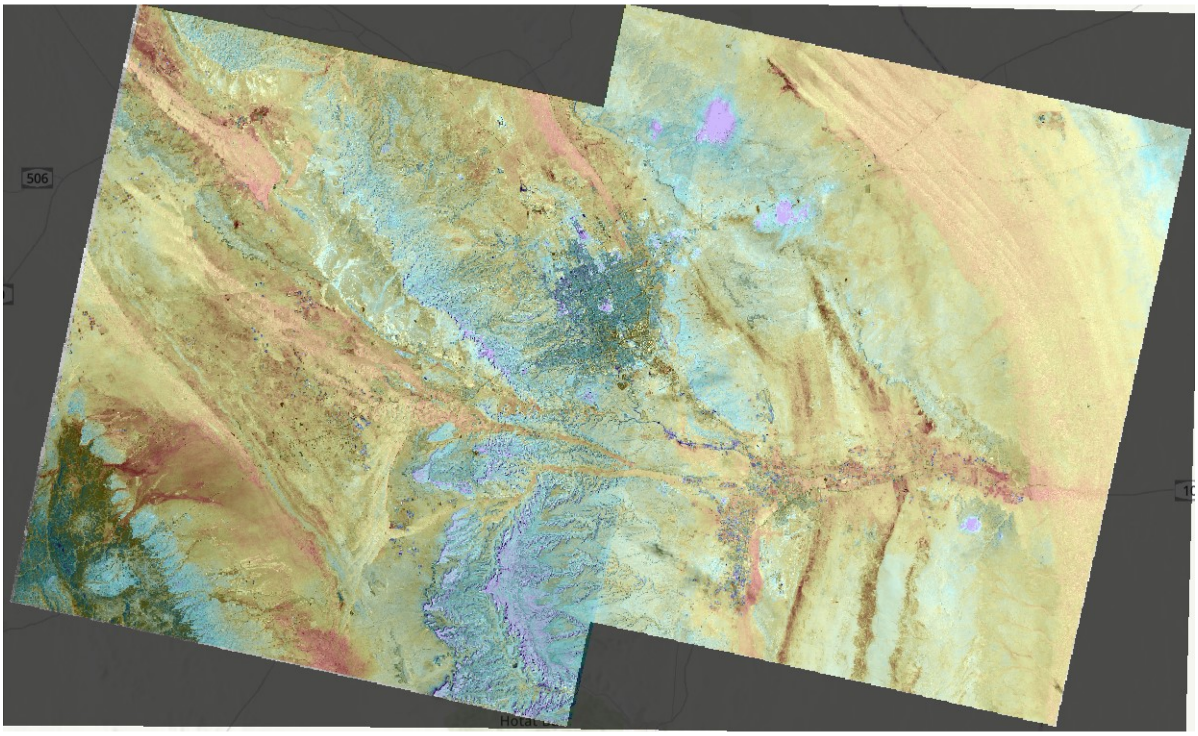


Figure F.1: Remote Sensing: LST across the wider region of Riyadh overlaid over a grayscale of the land use of Riyadh. The scale ranges from approx. 27°C (dark blue) to approx. 60°C (dark red). *ArcGIS*