QATAR UNIVERSITY

COLLEGE OF ENGINEERING

THE DESIGN, DEVELOPMENT, AND IMPLEMENTATION OF SMART GREEN ROOFS (SGR) IN HOT ARID CLIMATES - CASE OF DOHA, QATAR

BY

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ABSTRACT

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Title: The Design, Development, and Implementation of Smart Green Roofs (SGRs) in Hot Arid Climates - Case of Doha, Qatar

Supervisor of Dissertation: Fodil Fadli.

Greening the city is an old-conventional approach that has been rediscovered in the roof system to improve the urban environment in a smart and sustainable manner. Despite the growing literature on green roofs, there remains a lack of studies exploring the implementation of smart digital applications. Moreover, there is an absence of research addressing the utilization of smart green roofs (SGRs) in hot arid regions, making it challenging to evaluate their suitability as a heat mitigation strategy for Qatar. The SGR incorporates smart sensors linked to Internet of Things to automate optimal irrigation performance.

The research aims to design, develop, and implement SGRs optimal for the hot arid climate of Qatar. It seeks to evaluate the influence of SGRs on the users' thermal comfort and building's energy consumption, employing qualitative and quantitative tools. Employing questionnaire and interview approaches to gather users' perceptions. Real-time experiment and DesignBuilder simulations are utilized to compare an SGR against a non-green roof (bare) on an office building in Doha, Qatar. Real-time data measured plant performance, wind speed, temperature, humidity, and heat flux. Whilst simulation data extracted wind speed, temperature, humidity, heat flux, energy consumption, thermal conductivity, U-Value, and R-Value. Statistical analysis, *p* value tool, is employed to establish the significance and relationship between environmental factors and plant performance, including color, height, and leaf area index (LAI).

Performance of SGRs, associated with an increase in LAI and plant height, effectively reduced indoor temperatures, heat flux, and relative temperature. SGR's thermal performance improves with an increase in LAI, plant height, and soil moisture, reducing the U-Value and amplifying the R-Value. The resulting improved insulation directly influences a diminished amount of energy consumption. These effects enhance the users' thermal comfort concerning the indoor environment quality.

Urban planners, architects, and engineers can further implement the integration of the SGR as a valid green technology due to its lightweight element and low maintenance requirements. Finally, this study aims to design, develop, and implement SGRs and formulate design recommendations that can be applied on existing and new roofs in Qatar.

DEDICATION

This dissertation is dedicated to my loving family, who have been a source of strength, patience, motivation, and support for me through this entire experience. I am truly thankful and blessed to have you all in this dance called life, as I could not achieve what I am without you. Thanks for always standing by me.

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INTRODUCTION

Greening the building is an old conventional system that has been rediscovered to improve the damaging impacts on the environment. The greening concept has foundations in the biological and environmental nature, and can be further associated with architecture, design, and sustainability, mainly applied as part of the roof (Fadli, Bahrami, Susorova, Tabibzadeh, Zaina, & El-Ekhteyar, 2016; Fadli, Zaina, & Bahrami, 2019; Zaina, 2017). This research focuses on an integrated strategy to creating healthy urban environments and enhancing the quality of life by injecting the notion of smart green roofs (SGRs) with the integration of a sustainable approach. Green roofs are sustainable roof gardens which separates the substrate from the natural ground by at least one built structure (Grant et al., 2003). It is a horizontal surface covered and protected with plants on the exterior of the building (Rosasco & Perini, 2019; Yok & Sia, 2008). A roof allocates approximately 20% to 25% of the total urban surface and is not always the highest level of the building (Akbari & Matthews, 2012). This research follows a combined qualitative and quantitative methodology to compare and simulate an SGR against a non-green (bare) roof on a building in Doha, Qatar.

As a rapidly developing city, Doha, Qatar, is now facing a range of threats due to the expansion of suburban and urban environments. This fast growth and urbanization have led to increased energy use directly linked to climate change. Poor air quality and carbon dioxide (CO_2) emissions in the built environment are other threats from fast development. To further place the situation into perspective, Qatar’s industrial development is now at an unprecedented rate, with Doha being at the core of industrialization and urbanization. These developments have put the environment at danger as it threatens the biological diversity and ecosystem services. To eliminate these changes, the country of Qatar is developing management organizations and legislations that aid the ecosystem and initiates efforts toward preservation and conservation. Other factors affecting conservation efforts, despite regulatory procedures, include climatic and technical design factors. However, not all these implementations have yet shown desired results due to an absence of sufficient scientific and technical expertise. They may be attributed on the country's initial phase of environmental development. Regardless of the attempts, the uncertainty that has continued amongst policymakers remains in whether these regulations and laws will reduce the impacts industrialization has caused on the ecosystem and provide the proper safety from further damage (Susca et al., 2011). One potential is to inject life into the most deserted and neglected place in our buildings, the roofs.

The research aims to design, develop, and implement SGR in Qatar to mitigate the negative effect of extreme climates. Literature shows that green roof technology can address these issues and beyond (Dunnett & Kingsbury, 2004). The geographic location of Doha, with its hot arid climate, makes it a suitable case study location for green roof technology to study the impact of SGR installation truly. Green roofs are broadly known for energy saving capabilities around many nations world wide. They can employ a passive cooling method by absorbing the solar radiation that enters the building structure. In turn, the negative impact of buildings can also be minimized on the environment by using energy and material efficiently. On an urban scale, the thermal effect would be improved for the entire capital city, adding outdoor and indoor thermal comfort and improving air quality (Dunnett & Kingsbury, 2004). In addition, green roofs are closely linked to smart growth, green building practices, and sustainable or eco-cities (Yok & Sia, 2008). This allows focus on connecting the environment's inherent needs to the natural environment. Especially during the present time of the COVID-19 pandemic and extended lockdowns directly affecting people's health and access to the outdoor environment, smart green roofs can offer a gateway to improve air quality and reconnect with nature, revisit urban agriculture, provide contactless systems, and allow new spaces for social gatherings, accommodating an improved lifestyle. Following this line of inquiry, elaboration of the research components of problem, justification, aim, objective, and questions are stated.

The thesis structure is divided into three main parts, as shown in Table 1 and Figure 1. Part 1 gives an overview of the research context, case studies, background, and theoretical framework. Moving forward, part 2 illustrates the study details through research methods and tools, experimental setup, and data acquisition and analysis. Lastly, part 3 provides interpretations of the results and research findings, develops design recommendations, and concludes.

Table 1. Thesis structure

No. of Parts	No. of Chapter	Title	Description
Introduction	**Introduction**	Introduction	This section focuses on introducing the research problem, justification, aim and questions, and thesis structure.
Part 1: Green Roof Contextual Background and Theoretical Framework	**Chapter 1**	Green roof definitions, evolution, and taxonomy	This chapter presents the chronological evolution of green roofs, taxonomy of green roofs including green roof typologies, design consideration, and smart systems, and advantages and disadvantages of green roof systems.
	Chapter 2	Case studies of green buildings focused on green roofs	This chapter outlines an overview of case studies internationally, in the Middle East and North Africa (MENA) region, and locally in Qatar, ultimately leading to the development of a matrix of case studies on green roofs.
	Chapter 3	Theoretical framework	This chapter illustrates real-time-based and simulation-based research in hot arid climates for SGRs.

No. of Parts	No. of Chapter	Title	Description
Part 2: Research Methodology Development and Implementation	**Chapter 4**	Research method (design and stages)	This chapter illustrates a combined research method including an overview of qualitative and quantitative tools, with a focus on DesignBuilder software.
	Chapter 5	Experimental setup of the use-case	This chapter illustrates Qatar meteorological data, study area, selection criteria, justification, building envelope, and SGR application use-case in Qatar.
	Chapter 6	Data acquisition and analysis	This chapter demonstrates the qualitative data including interview responses, quantitative data including questionnaire answers, performance, behavior, and monitoring of plants, irrigation system, temperature, humidity, wind speed and heat flux, and simulated data regarding temperature, humidity, wind speed, thermal conductivity, U-Value, R-Value, heat flux, and energy demand.
Part 3: Results Interpretation, Conclusion, and Future Directions	**Chapter 7**	Results interpretation and research findings	This chapter analyzes the collected real-time data and generated simulated data. It incorporates an interpretation of the SGR study, performance of plants, smart irrigation system, cooling load, energy consumption, and user thermal comfort. The use of the statistical significance *p* value tool allows to determine relationships between environmental variables and plant performance parameters. Moreover, it calibrates results of the simulated data against the real-time data.
	Chapter 8	Conclusion and smart green roof design recommendations	This chapter consist of the conclusion of the dissertation, study limitations, and future directions for further research and investigations. It further presents SGR design recommendations for a balanced solution between the user's thermal comfort and building energy consumption in a hot arid climate through installation of SGRs.

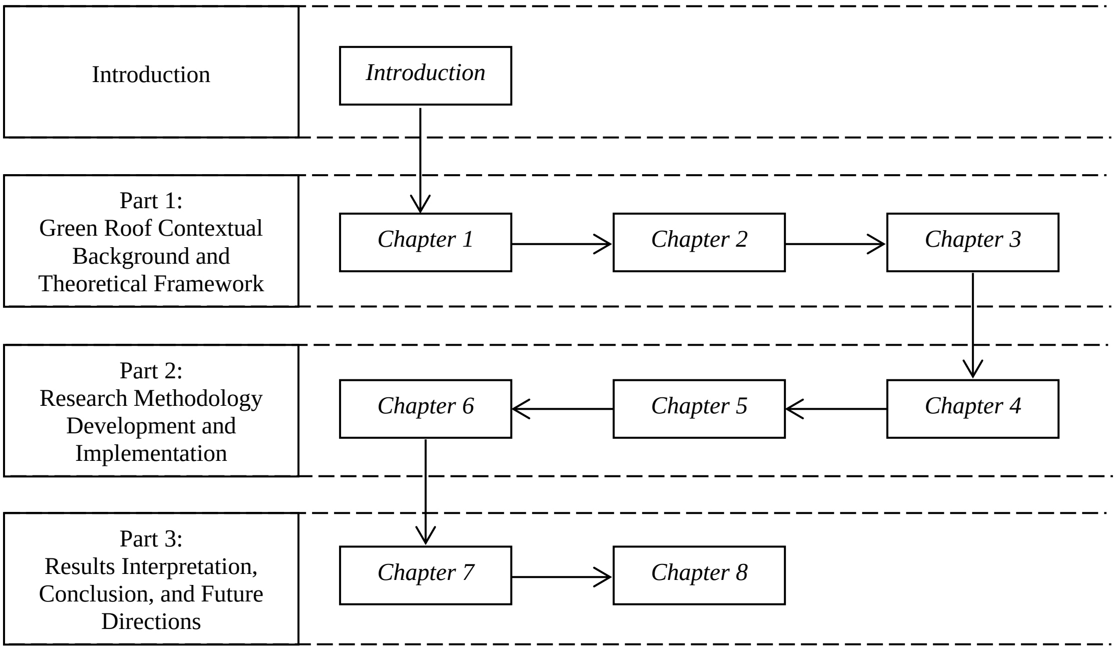


Figure 1. Thesis structure.

I. Research Problem

Most surfaces in urban areas are composed of concrete, stone, and tarmac, with a small amount of green space area (Croce & Vettorato, 2021). Furthermore, the hot climate of Qatar is not cooperative as extreme climate states of high solar radiation and external air temperature cause massive heat gains via building structures. In this climatic zone, buildings utilize immense energy to cool the area through AC systems mechanically. On another note, most climatic issues worldwide result from urbanism and a lack of integration of natural resources (Long, 2014). Moreover, the urban areas' built environment increases the outside air temperature and relative humidity, therefore resulting in the urban heat island effect (UHI). The UHI increases air pollution and causes global warming at the urban scale (Tzavali et al., 2015).

There is a lack of successful green roof systems in the Gulf and the Middle East and North Africa (MENA) region, along with an absence of the utilization of smart digital applications for systems with green roofs. These aspects are highlighted and studied in this dissertation's literature and case studies section, presenting a gap in knowledge. Identifying this gap allows this thesis to delve into the scope for further exploration of SGR design and implementation appropriate for the hot arid climate of Qatar. This topic may be understudied because research on the cooling effects of green roofs has primarily been theoretical by only relying on growing mediums such as soil (Eumorfopoulou & Aravantinos, 1998). The lack of experimental data and research in other hot arid climates, such as those in Qatar, makes it difficult to evaluate the suitability of green roofs as a heat mitigation strategy for Qatar. Thus, an experimental study into the design, development, and implementation of the performance of an SGR is needed to evaluate its suitability in Qatar and to quantify associated energy savings. To account for the differences in climate as well as variations in performance-related parameters, computer simulations are utilized. Data collected and analyzed will help designers make better decisions in the future and establish the needs of SGRs as a passive cooling technique for the region.

Furthermore, the world is moving toward contactless solutions as well as smart systems due to the current context COVID-19. A need has risen to ensure safe and clean contact to prevent future pandemics. One such probable solution is the invention of contactless methods to reduce the transfer of bacteria between users. The use of smart technology and digital applications on green roofs enhances the building structure by stimulating self-sufficiency, independency, and adaptability to future crises.

Besides the technology and system development of green roofs, the research by Hossain et al. (2019) concentrates on potential obstacles the construction industry may face in using green components in building designs. The outcomes show a gap in knowledge of the construction of green components, which becomes a major drawback to implementing green architectural components (Hossain et al., 2019).

II. Research Justification

Well-established, developed, and successful green roof case studies, as indicated by Hansen (2018), have shown great results in Germany and Switzerland over many years. Conversely, there are not many green architectural components in the MENA region. However, the potential for this is due to many hectares of existing roofs in the MENA region that can be planted with minor or no structural adjustment. In addition, vertical green walls, terraces, and horizontal green roofs offer a valued green space in cities where populations are rapidly increasing, considering land is difficult to afford on the ground. Smart green roof (SGR) systems can improve the city's microclimate, improve heat waves, mitigate the UHI effect, and transform radiation into useful outputs. This study becomes crucial to convince stakeholders and the general public of the need for SGRs in cities, evaluating the different components and construction types of green roofs compared to bare roofs.

With the implementation of an SGR, this change to the Qatar climate is bound to have ramifications as it indirectly addresses sustainability, environmental comfort, built environment aesthetics, emerging smart technologies, eco-cities, and environmental behavior issues. Utilizing SGRs means better management of all aspects of the system of green roofs. In particular, a more robust management of water irrigation, use, and quantity is solidified. It is essential to consider controlling water requirement more efficiently against water vulnerability.

By 2050, the population in the world is predicted to increase from 7.7-9.7 billion, and continuous fresh water needs are contributing to an increase in water shortage (United Nations, 2019). Water sustainability is thus critical, described as the continuous provision of clean water for user consumption and the needs of other living things. This is an important standpoint for the success of Qatar, where it is currently in jeopardy (Darwish & Mohtar, 2013; Fadli et al., 2016). This hot and arid region encounters extreme and harsh environments with minimal rainfall and high temperatures. According to the literature, watering plants is directly linked to water shortage in severe climates. (DeNicola et al., 2015). Water must be provided efficiently to accomplish the advantages of green construction through sustainable means. The introduction of SGR irrigation practices offers a potential means to replenish water sources. Therefore, it is crucial to recognize the challenges of water accessibility and the relevance of SGRs in Qatar.

Qatar is a hot arid country with a fragile and harsh environment, low annual rainfall (82mm on average) and high annual evaporation rates (2,200mm on average), high summer temperature (>40˚C), and low soil nutrient availability. Water sources including groundwater and rainfall are limited (Darwish & Mohtar, 2013). Thus, conserving water for SGRs in a sustainable way and using it for green constructions is crucial for the context of Qatar. As indicated in Figure 2, continued economic and population growth presents additional concerns about the security of the water supply (UnitedNations, 2021).

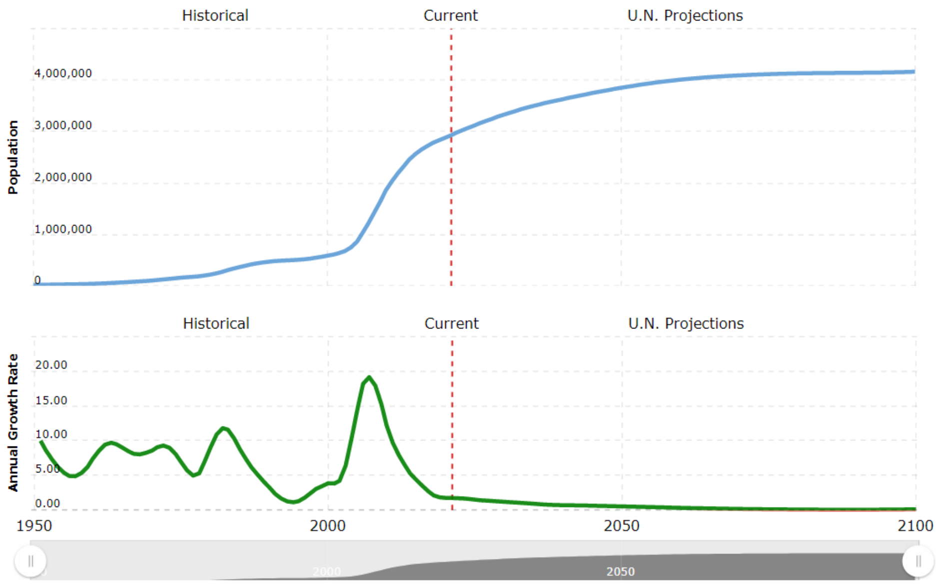


Figure 2. Qatar’s annual population growth rate with United Nations Projections (Source: United Nations, 2021).

Related to water security concerns, Qatar must take substantial procedures to implement water conservation measures and create an integrated management water program. This can be done, for example, by reducing irrigation demand. On the other hand, studies show that more water may be allocated to irrigation operations by improving water conservation measures such as using treated sewage effluent (TSE) and restructuring water pricing (Mazzoni et al., 2022). As presented in Figure 3, the water consumption for agriculture increased until 2015 as an economic activity (MME et al., 2017). Even though majority of Qatar's wastewater is treated and utilized for the purpose of irrigation, the following measures can effectively control irrigation water needs to combat water scarcity and risk. These measures include creating an integrated approach to managing water resources and implementing smart, innovative technologies.

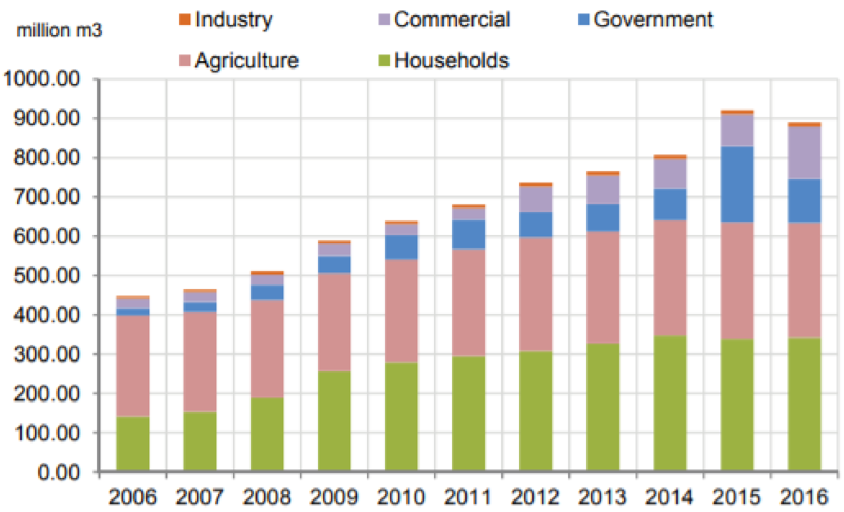


Figure 3. Qatar's water use by economic activity from 2006-2016 (Source: MME et al., 2017).

Implementing smart technologies for green roofs protects plant and SGR investment, further minimizing water wastage. The Qatar Development Strategies and Qatar National Vision have recognized how crucial it is to achieve water security. Issues of maintaining water security involve resolving encountered problems such as the following: (1) inconsistent water monitoring according to variations in the amount of soil moisture that plants require; (2) lack of systematic technological tools to communicate unpredicted changes in temperatures or weather; and (3) manual estimate or incorrect estimate of some plants' water requirements (overwatering) to attain high rate of productivity. Accordingly, as stressed by the Qatar National Development Strategy (QNDS) and Global Sustainability Assessment System 2019 (GSAS), effective watering practices through smart technologies of greening and advanced irrigation techniques make a sustainable enhanced environment. SGR technologies not only resolve these unique challenges but seeks techniques for high-energy performance that conserve energy, architecturally remarkable, and environmentally friendly (Thornbush, 2015).

III. Research Aim and Questions

The main aim of this study is to design, develop, and implement an SGR in Qatar's buildings to enhance the user's thermal comfort and provide solutions regarding building energy consumption in the built environment (Figure 4). Hence, the main question shaping this research is: how do SGRs influence buildings' indoor and outdoor properties in the hot arid climate of Qatar, and what is their effect on improving energy demands and thermal comfort? More precisely, this study aims to answer the following questions:

1. How to design SGRs in the hot arid climates of Qatar
2. How to develop SGRs?
3. How to implement SGRs in Qatar's hot arid climate?

The following research framework has been developed to answer these questions, divided into three main sections (Table 2).

Table 2. Research questions, aims and objectives, and methods

	Research Questions	**Aim and Objectives**	**Methods**
Design	How to design smart green roofs in the hot arid climate of Qatar?	Design a smart green roof system based on relevant parameters.	- Review the chronological development of green roofs over architectural eras. - Review the different taxonomy of green roofs, including roof typologies, design considerations, and smart systems in terms of climatic performance and efficiency. - Review advantages and disadvantages of green roofs. - Explore and discover recent and existing urban green architectural components adopted to apply the most suitable type of green roof on buildings in hot arid regions. - Understand the users' perception and thermal comfort to assess the building's indoor environment quality. - Analyze experts' perceptions on the application of SGRs and determine the level of knowledge and challenges Doha faces in using SGRs.

	Research Questions	Aim and Objectives	Methods
Develop	How to develop smart green roofs?	Develop a smart green roof inclusive of all pertaining systems.	- Develop a smart green roof to enhance the quality of buildings in a contactless aspect using real-time and simulation tools.
Implement	How to implement smart green roofs in Qatar's hot arid climate?	Implement smart green roofs and formulate design recommendations.	- Calibrate and validate the real-time results of the use-case study analyzing the weather data and environmental performance of bare and SGRs on the office building using computational (DesignBuilder) for one year. - Evaluate and analyze the optimum energy consumption, including thermal performance and cooling loads according to relevant SGR parameters through the simulation-based tool by looking into orientation, weather conditions, different types of the building (green vs. bare roof), U-Value and R-Value, density and soil thickness, and types and characteristics of plants. - Appraise how plants affect a building's microclimate and thermal efficiency. - Simulations and parametric analysis results will be used to measure the effects of smart green roof systems on reducing the building's energy consumption and thermal performance. These findings allow for the formulation of design guidelines for implementing smart green roof systems.

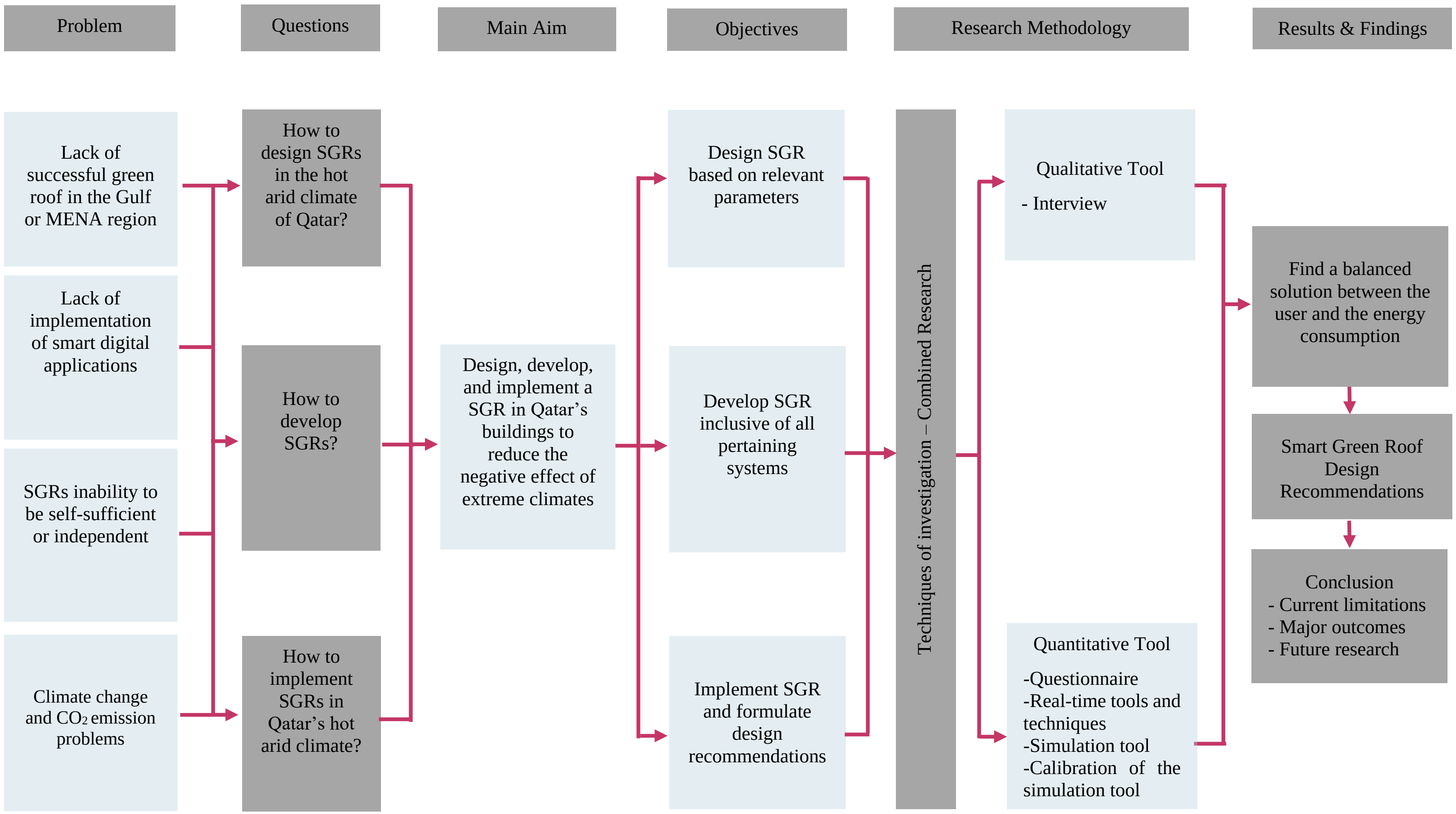


Figure 4. Thesis framework diagram.

PART 1: GREEN ROOF CONTEXTUAL BACKGROUND AND THEORETICAL FRAMEWORK

PART 1 INTRODUCTION

Chapter 1 deals with framing and directing the use-case research from reliable literature sources. The advantages and disadvantages are pinpointed by defining the terms and looking into the historical significance of green roofs and their evolution through time.

The second chapter takes a focused lens and examines case studies of green roofs in hot and arid regions. From a broad viewpoint, this is achieved by looking into international green roofs, then a more regional perspective, ending with a local Qatar focal point.

Chapter 3 elaborates on this supplied conceptual information integrating all aspects discussed in chapter 1. Resulting in a theoretical framework of real-time and simulation based research with a particular interest on building energy consumption and users' thermal comfort (Figure 5).

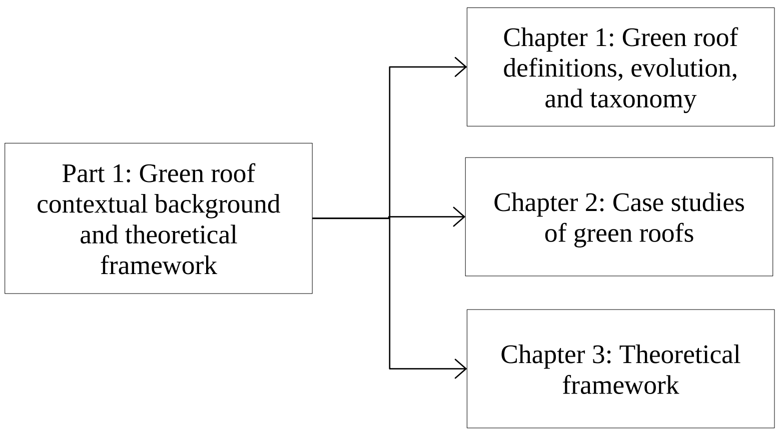


Figure 5. Part 1 green roof contextual background and theoretical framework.

CHAPTER 1: GREEN ROOF DEFINITIONS, EVOLUTION, AND TAXONOMY

1.1 Introduction

Recent studies suggest that installing green roofs on buildings in urban areas confer a strong association for environmental advantages. They are associated with reducing stormwater runoff, carbon dioxide, UHI effect, and energy consumption (Santamouris, 2014; Suszanowicz & Kolasa-Więcek, 2019). In order to understand the potential role of smart green roofs (SGRs) on Qatar's climate, this section identifies the chronological evolution of green roof development and use in the MENA region; taxonomy of green roofs that are ideal and appropriate for Qatar, including typologies, design considerations, and smart systems; and advantages and disadvantages of green roofs; shown in Figure 6.

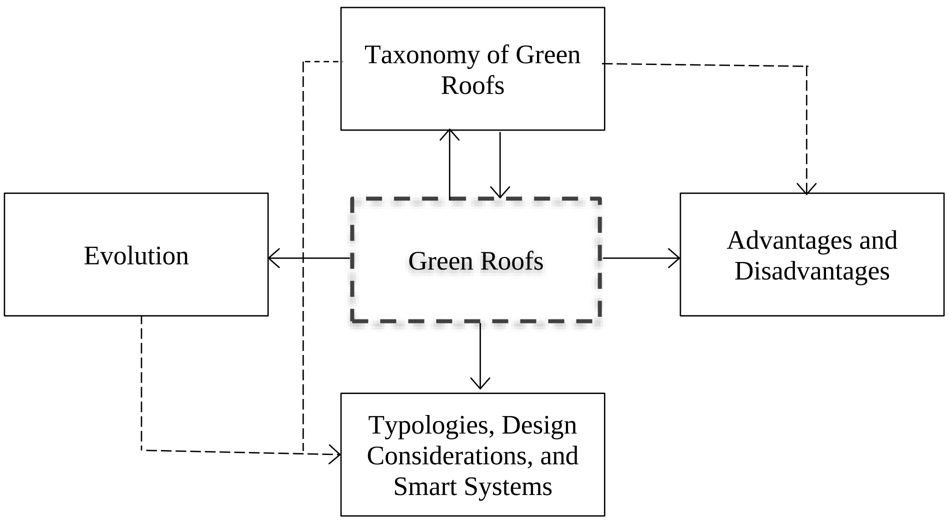


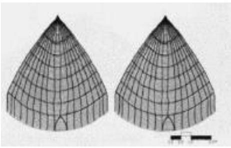
Figure 6. Green roof context and systems structure.

1.2 Chronological Evolution of Green Roof

Green roofs' chronological evolutions to most recent developments have been systematically and chronologically referenced and discussed in the literature. A summary of the history and significance of green roofs in hot climates is provided in this section (Mediterranean, tropical, steppe, and hot climate). These climates implemented green roofs on the building structures or upper-ground gardens in Africa, Asia, Eurasia, Australia, and America. Using plants through architectural means and implementing green roofs are not new notions (Grant et al., 2003). There have been high structures of greenspace for since humankind have been interested in architecture (Velazquez, 2005). Examples of green roof development of vernacular and monumental architecture in a hot climate are given in Table 3 and Figure 7. Green roof technologies and recent applications in the MENA region will also be reviewed to achieve Qatar's more holistic and climate-specific SGR application.

Table 3. Green roof development of vernacular and monumental architecture in a hot climate

Era	Image	Location	Description
Around 2100 B.C.	 (Edge, 2020)	Sloping walls of the Ziggurat of Nanna	Covered with shrubs and trees formed by a stepped pyramid
Around 600 B.C.	 (Christopher Klein, 2018)	Hanging Gardens of Babylon	-Roof gardens and luxurious terrace -Different plant types that did not natural exist in the area were cultivated

Era	Image	Location	Description
Around 200 B.C.	 (Ide, 2015)	Italy's Villa Dei Misteri (Villa of the Mysteries)	Intensive hanging roof gardens and outer facades
19th century	 (Abass et al., 2020)	Africa	-Dwelling shape is in the form of a dome - Dry reeds and grass serve as the structure's construction material -Round-geometrical shapes -Thatched roofs used since ancient times until present time to eliminate hot climatic conditions
19th century	 (Abass et al., 2020)	Central Europe	-Thatched roof used to prevent heat from the building -Grass hunts used by farmers as shelter and storing area
19th century	 (Abass et al., 2020)	North America	-Dry turf used as a construction material -Grass used at the steep cover roof and to palm leaves from exterior climate
2010	 (Johnsen, 2010)	North American and Europe	Incorporated intensive and extensive flat green roofs to decrease effects of imperviousness caused by urban growth and development
2015 - Ongoing		Hot arid regions	Excessive research on each component of flat green roofs with solar panels; how to make more cost-effective designs of green roofs under extremely hot arid climate conditions all around the world is in progress

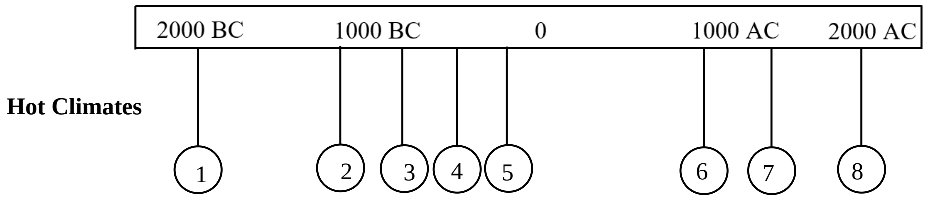


Figure 7. Timeline of the main milestones showing the existence of green roofs throughout history for hot climates (Adapted from: Alexandri, 2005).

Note. (1) Ziggurats, Mesopotamia; (2) Thatched roofs and buildings in Africa, Asia, Latin America, the Mediterranean, and Australia; (3) Hanging Gardens of Babylon; (4) Palace, Persepolis; (5) Villa of Mysteries, Pompeii; (6) Roof gardens of Tenochtitlan and Yucatan; (7) Towers in Italy; (8) Churches and Mosques, Africa.

The first evidence of a green roof with trees and shrubs was found on the Ziggurat of Nanna's sloping walls, around 2100 B.C. The Hanging Gardens of Babylon in Iraq included luxurious terraces and roof gardens around 600 B.C. This early form of green roof insulation was introduced in an intense and harsh climate (Reade, 2000). Later, in the Mediterranean era, around 200 B.C., Italy's Villa Dei Misteri (Villa of the Mysteries) incorporated roof gardens with intensive hanging roof gardens and outer facades (Maiuri, 1960).

Later, in the early 1800s, Northern US and Canadian settlers presented grass roofs and walls. In the 19th century, the Maya buildings in the Yucatan peninsula had intensive tropical roof gardens, such as the Chichen Itza Yucatan (Yampolsky & Sayer, 1993). In addition, Africa has used grass roofs since antiquity, usually built with a thatched conical roof, such as the Shrine of God Menes in ancient Egypt, and a beehive thatched roof, such as the Seno Palel Mosque in Senegal (Alexandri, 2005). Thatched roofs, made of grasses, palms, leaves, and reeds, became essential elements of vernacular architecture in Africa and Asia. It was a readily available construction material and an insulator from solar radiation (Alexandri, 2005). Until the 19th century, roof thatching was widely used in most of central Europe, Austria, and Australia (Alexandri, 2005). At the same time, dry turf roofs have been used in North America and Canada (Alexandri, 2005).

Although 'Rooftop gardens' are quickly adopted in western urban settings, not much about their performance is known regarding hot and arid climatic conditions where access to water is restricted and a plant's survival is determined by the severity of the drought. Over an extended period, these regions' geography and climate have led to water shortages and resource-conscious water management. Accordingly, countries in hot arid zones such as Egypt, Dubai, and Kuwait started implementing green roofs.

Today, the possibilities of using green roofs in hot and arid climates have been studied to showcase the available technologies. Recent studies in such regions, such as the Kingdom of Saudi Arabia, have shown that green roofs reduce the average heat load of existing buildings by adding an extruded polystyrene, insulated polystyrene layer, and polyurethane in the roof system (Al-Sanea et al., 2012). Another research conducted in Qatar by Andric et al. (2020) utilized green roofs and evaluated their energy consumption performance. Reducing energy use to 3% was achieved using expanded polystyrene insulation.

Other smart technological advancements, such as drip and sprinkler irrigation methods and low-cost sensors that minimize surface runoff and water use, have made green roofs extremely useful. This includes fuzzy logic irrigation technology, improving irrigation scheduling, and determining needed water coverage (Selmani et al., 2019). Along with the Internet of Things (IoT), analyzing soil and climate conditions through sensors and controllers, thus optimizing green roof performance. In recent literature, García et al. (2020) explore the prospect of Artificial Intelligence (AI) obtaining information about plant growth and determining optimal water, fertilizer, and energy needs.

Finally, it is essential to note that there is a lack of research and literature concerning the concept of green roofs in hot arid regions, specifically those with smart-based applications, likely due to the technologies and innovation of green roofs being novel. However, recent and emerging implementations of horizontal green roofs and vertical green walls have been spotted in Qatar's public areas (Fadli et al., 2019). This has been observed in Katara and the Pearl (Viva Bahriya area), respectively. To summarize, studying the timeline of events for green roofs throughout history could ensure a clear direction for future research. The history of green roof technology predates the modern era. Many of the purposes of green roofs used throughout history are similar to those today. According to literature review, the deployment of green roof technology is justified due to the numerous and well-documented benefits that these systems may provide to the urban environment. Green roofs have a long history, and our ancestors employed them to control the temperature of the surrounding environment.

In comparison to most other structures, green roofs make buildings warmer in winter and cooler during summer. Green places make people feel better and make our lives better; however, these parameters are difficult to quantify. Moreover, the careful examination of historical aspects of green roofs gives a better context and understanding of SGR design and implementation in the MENA region. Thus, this section aims to provide evidence, confirm, and understand the potential adaptation and application of the green roof process to effectively implement SGRs in Qatar's vast urban region in a sustainable manner.

1.3 Taxonomy of Green Roofs

The taxonomy of green roofs, as shown in Figure 8, is divided into three sections, including green roof typologies, design considerations affecting green roofs (geographic location, structural systems, and plants and growing medium), and smart systems of green roofs (importance and relevance of SGRs, conventional and smart irrigations systems, smart irrigation systems and trends of smart systems, and innovative smart system outcomes based on morphological thinking).

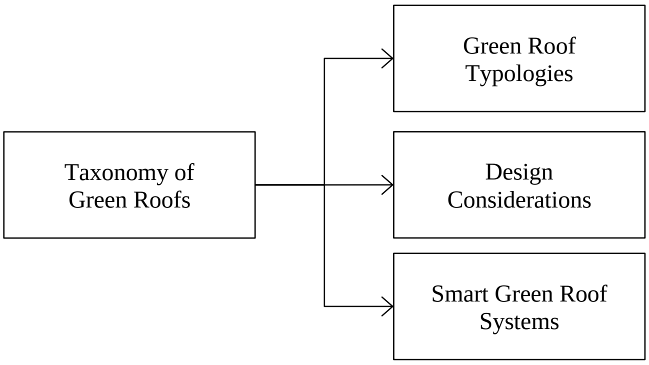


Figure 8. Taxonomy of green roofs (Adapted from: Alexandri & Jones, 2008; Amorim & Mendonça, 2017; Bauder, 2019; Vijayaraghavan, 2016; Tolderlund, 2010; Zaina & Fadli, 2020; Hossain et al., 2019; Velazquez, 2005).

1.3.1 Green Roof Typologies

This section develops a technical review of the taxonomy of green roofs using a strengths, weaknesses, opportunities, and threats (SWOT) analysis. These aspects have been reviewed with the lens of a specified objective to understand green roofs' advancements, literature, and technicalities in a hot and arid climate. This is essential as there is a lack of literature and implementation of green roofs in these climates, particularly in the Gulf and Qatar. Thus, investigating the types of green roofs provides context to design, develop, and implement SGRs appropriately. This paper further offers a potential contribution to the literature by reviewing the limitations, challenges, opportunities, and capabilities of green roofs under conditions of hot arid regions, where roof systems can helpfully impact environmental change.

As a protective agent against water and roots, the green roof, with its several layers of insulation, filtration, and drainage system, allows medium-sized plants to grow safely on the roof's surface. A green roof can be classified into five categories: (1) eco-roofs or roof gardens (large-scale form of the roof garden, but due to cold weather factors, the green cover does not cover it other than specific periods of the year); (2) brown-roofs (a roof that contains soil that is left without a plantation, and over time the roof is grown automatically with the frequency of wildlife represented by birds and other animals on the roof surface); (3) intensive green roofs; (4) extensive green roofs; (5) combination of extensive-intensive assemblies; and (6) cool roof with photovoltaic solar panels (Zaina & Fadli, 2020). This research aims to evaluate an appropriate green roof that will achieve efficacy in the hot and arid climate of Qatar and the MENA region.

Eco-roofs, brown-roofs, intensive green roofs, and cool roofs require a vast water supply, structural roof reinforcement, and maintenance (Bates et al., 2013; Reyes et al., 2016). Both Bates et al. (2013) and Reyes et al. (2016) report lightweight extensive green roofs composed of a substrate layer less than 20cm, thus requiring minimal or no irrigation and minimal roof maintenance and structural support. All roof typologies, except extensive green roofs, are heavyweight due to the deep soils and plant. Without further consideration of structural reinforcement, the building may not withstand the additional weight and potentially collapse (Bates et al., 2013).

A study by He et al. (2020) evaluated the implementation of green roofs and cool roofs in the summer and winter of metropolitan cities. Beyond the cooling roof's effectiveness at reducing high temperatures during the summer, green roofs advantage lies in that they produce fewer adverse effects on other climate conditions (He, Zhao, Zhang, He, Yao, Ma, & Kinney, 2020). Additionally, green roofs provide building insulating effects from the soil substrate and plants, while other roof types do not (Coutts et al., 2013).

Out of the green roof classified types, two main green roof designs function year-round, contain plantations, and are most often implemented in buildings. The two main types include (1) extensive green roofs, which typically have soil profiles that are relatively shallow, with soil depths between 10-25 cm, and (2) intensive green roofs, which are highly complex and have extremely deep soil profiles (up to 30cm) and extremely deep heights (Dowdey, 2017), as depicted in Figures 9 and 10. Table 4 highlights the main criteria for comparison amongst both extensive and intensive green roof systems.

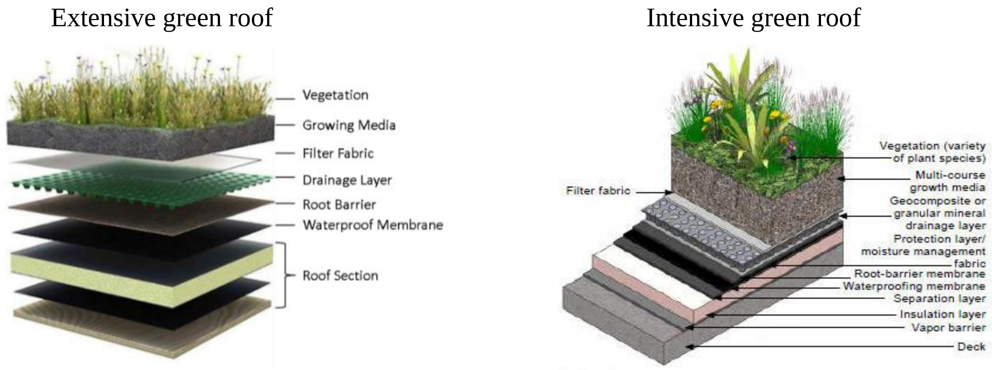


Figure 9. Construction of extensive and intensive green roof types (Source: Greenheights, 2012).

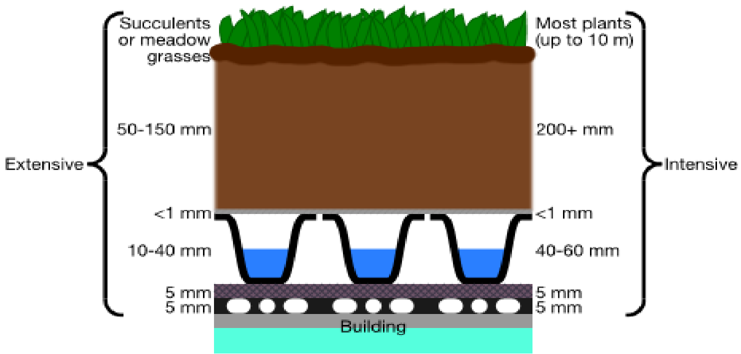


Figure 10. Depths of extensive and intensive green roof layers (Source: Vesuviano et al., 2014).

Table 4. Taxonomy of extensive and intensive green roof types and their main attributes (Adapted from: Hossain et al., 2019; Velazquez, 2005)

Attributes	**Extensive (Low Profile/ Eco-roofs)**	**Intensive (High Profile/ Roof Gardens)**
Thickness of growing media	Thickness 10-25cm	Thickness 30cm and deeper
Diversity of plants	Fewer plants variety (low-growing plants: alpine types, herbs, succulents, grasses, and mosses)	Enormous plants options, depending on loads, design, and budget (big plants, shrubs, trees)
Accessibility	Often not accessible	Often accessible: designed for user recreation
Roof Slope	Up to 30° and higher	Almost flat
Construction	Moderately easy	Technically complex
Weight	Low weight 60-150kg/m^2	Greater weight above 300kg/m^2
Maintenance	Simple and low	Complicated and high
Cost	Low capital cost 130-165$/m^2	High capital cost 540$/m^2
Irrigation	Low irrigation, nutrient, and maintenance	High fertigation, irrigation, and maintenance
Water	Retains water from 27-45l/m^2	Retains water from 70-130l/m^2

To improve the urban environmental quality, existing roof tops are essential. Table 5 summarizes indoor and outdoor factors that are correlated with extensive and intensive green roofs using the SWOT principles.

A SWOT analysis method exploring green roofs for hot and arid climates allows to address weaknesses, deter threats, capitalize on opportunities, and view strengths. As a strategic approach, SWOT analysis helps to identify resources, limitations, and capacity to implement SGRs in Qatar. By analyzing the overall data on the structure of green roofs, a comprehensive and objective framework can be achieved regarding extensive and intensive green roofs.

Table 5. Strengths, Weaknesses, Opportunities, and Threats analysis for extensive and intensive green roof types (Adapted from: Hossain et al., 2019; Velazquez, 2005)

Green Roof Type	SWOT Factors	Positive	Negative
Extensive	**Indoor Factors**	Strengths - Low thickness - Low weight - Fewer nutrients - Low maintenance - Low capital cost	Weaknesses - Not accessible (slopes up to 30° and higher)
	Outdoor Factors	Opportunities - Low irrigation	Threats - Low growing and less variety of plants
Intensive	**Indoor Factors**	Strengths - Accessibility (flat surface)	Weaknesses - High thickness - Greater weight - High capital cost - High fertigation - High maintenance
	Outdoor Factors	Opportunities - Big growing and more plant variety	Threats - High irrigation

The strengths of an extensive green roof system are low thickness, nutrients, weight, cost, and maintenance. An extensive green roof can be considered roof finishing or building material. It requires almost no irrigation, nutrients, or maintenance. An extensive green roof's weakness is that it is inaccessible in most conditions, as it has a steep slope of up to 30° and higher. The cost of developing green roofs depends on various components, such as the plants, soil, quantity of drainage system, and type of the roof membrane. As presented in the Environmental Protection Agency report (2009), it was indicated that the initial expenses for an extensive green roof are USD 10/m^2 (Shafique et al., 2018). In Qatar, the maintenance costs of an extensive green roof reduce when plants cover the entire roof.

According to the SWOT analysis, external factors comprise the opportunities and threats the environment presents. Although the limited low-growing choice of vegetation and a restricted variety of plants is a threat; however, this is a chance for extensive green roofs as plants would have soft-delicate and short roots, being able to survive without regular irrigation.

Whereas, regarding intensive green roof systems, easy accessibility is a strength as the roof is flat. On the other hand, high thickness, weight, cost, and maintenance are weaknesses of this system. In many cases, building structures should be constructed to support the additional weight. Fertilization and weeding maintenance are needed for a more than 30cm soil profile, incorporating a wide selection of plant choices, including grass, bushes, or trees (Vijayaraghavan, 2016). As reported by the Environmental Protection Agency (2009), an estimation of initial cost for an intensive roof is up to USD 270/m^2 (Shafique et al., 2018). The maintenance expenses of an intensive green roof remain constant when plants cover the whole roof of a building in Qatar.

Large growing and various plants are an opportunity for the environment and ecosystem. The intensive green roof system offers these environmental strengths; however, it also becomes a risk as it involves frequent watering.

Both extensive and intensive green roofs have similar strengths for the cities' environment with a different impact. For research purposes and in support of the study hypothesis, SWOT analysis depicts extensive green roof systems as appropriate to implement in Qatar’s buildings. Unlike intensive green roofs' difficulty in application, extensive green roofs have the potential to provide sustainability to Qatar’s green infrastructure. Furthermore, intensive green roofs need deeper soils, indicating more mass; thus, the structure of the existing building must bear the roof’s load, which is potentially deemed dangerous. In this case, the intensive green roof systems-wide variety of plants is not considered a priority, especially since most green roof plants do not survive in Qatar's hot and arid climate. Plants that survive in Qatar’s environment can be sustained through extensive green roof systems (Angus, 2020; Saeid, 2013; Schweitzer & Erell, 2014; Vijayaraghavan & Joshi, 2014). Thus, the focus of this research relies on the exploration of a green vegetated extensive SGR system.

1.3.2 Design Considerations for Green Roofs

Urban planners and architects have proposed green sustainable approaches to solve the problems. Green roofs act as a sustainable building design component, gaining importance and being gradually applied over the years (Hopkins & Goodwin, 2011). The full potential of a green roof system is a much-established practice worldwide (Perini & Ottelé, 2014; Radić et al., 2019); however, it is not fully exploited in hot arid regions. This is partly due to the lower variety and type of plants that can be utilized and selected for a particular type of green roof construction in hot arid regions. Moreover, the effects of green roof systems are rarely mapped (Radić et al., 2019). Occasionally, climates in which green roofs are studied are not specified in researches, and assessment approaches are not always precise (Radić et al., 2019).

Understanding design considerations and their influence on the measures needed aids the implementation of an SGR system in the hot arid region of Qatar. The design and construction of an SGR depend on the purpose and the expected performance (VanWoert et al., 2005). These performances are to achieve essential positive impacts, including mitigation of the UHI effect, reduction of carbon dioxide, decrease in stormwater runoff, improved air quality, improved energy efficiency, noise reduction, increased biodiversity, aesthetic appeal, positive social aspects and educational impact, psychological effects on urban dwellers, and enhancement of user health, comfort, and wellbeing (Attia, Beltrán, De Herde, & Hensen, 2009; Zaina & Fadli, 2020). Factors to design a green roof can be grouped into the categories outlined in Figure 11, including geographic location and climatic conditions, structure, plants, and growing medium.

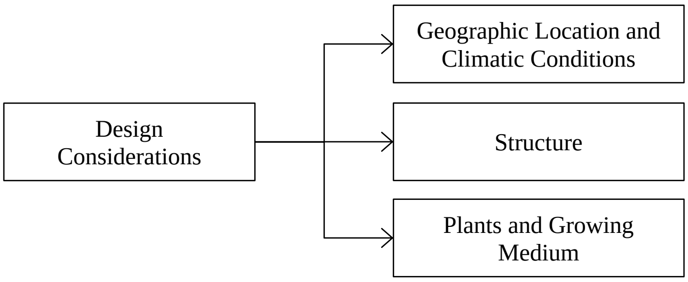


Figure 11. Design considerations of green roof design (Adapted from: Alexandri & Jones, 2008; Amorim & Mendonça, 2017; Bauder, 2019; Vijayaraghavan, 2016; Tolderlund, 2010; Zaina & Fadli, 2020).

1.3.2.1 Geographic Location and Climatic Condition

The factors associated with geographic location include climatic zone and conditions such as exposure to sunlight, wind advantage, rainfall volume, temperature, humidity level, and climatic condition (Alexandri & Jones, 2008; Bauder, 2019). Other factors include the cardinal direction the roof faces, affecting light radiance and heat striking green roofs (Figure 12).

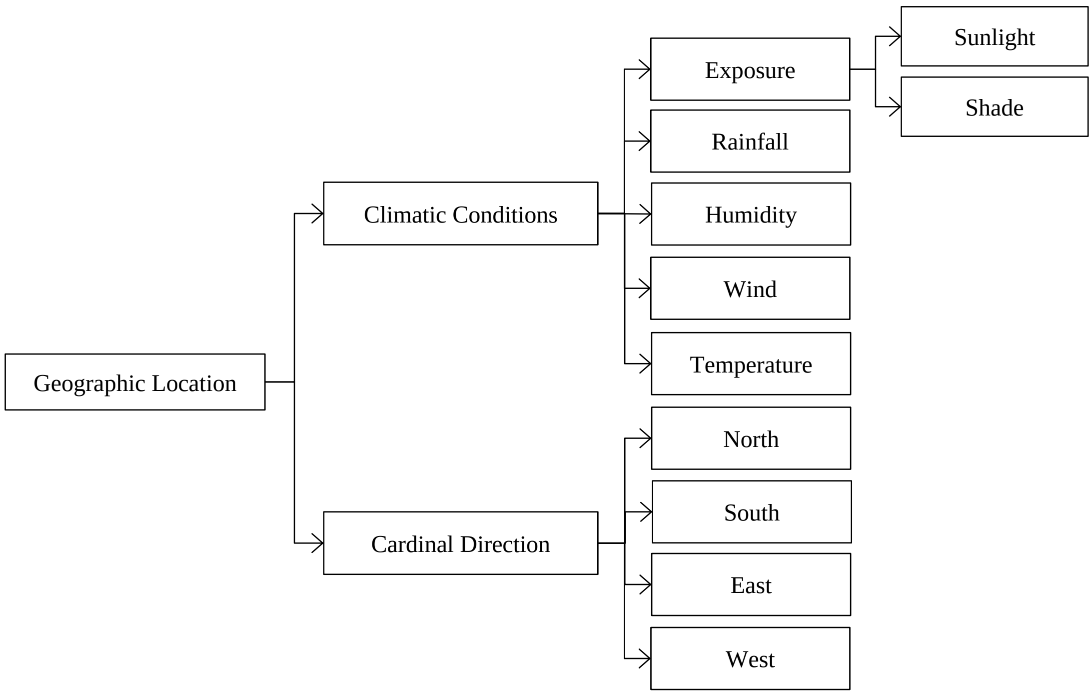


Figure 12. Geographic location factors affect design considerations of a green roof (Adapted from: Alexandri & Jones, 2008; Shafique et al., 2018).

1.3.2.2 Structural Systems

The function of the green roof, dependent on design considerations, is determined by the structural components, as illustrated in Figure 13 (Zaina & Fadli, 2020). As a by-product of its arrangement, the layout and configuration of the green roof layers significantly influence environmental advantages based on climatic and locational conditions (Alexandri & Jones, 2008; Bauder, 2019). Each component is affected by numerous elements and must be selected appropriately to achieve optimal results.

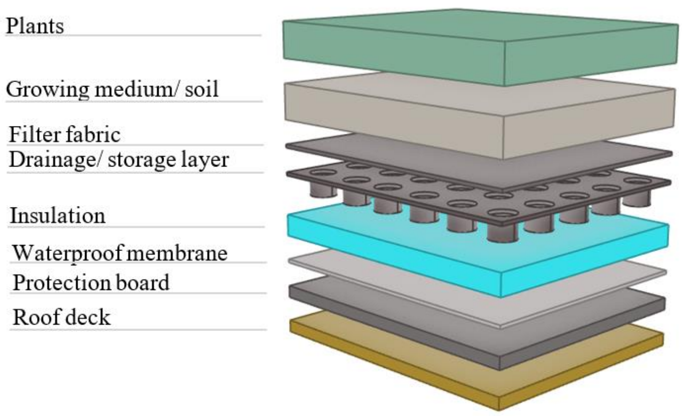
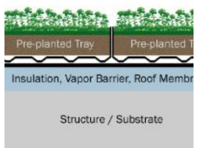


Figure 13. Typical section of a green roof system.

The construction types for extensive green roof systems differ. Different construction systems, strategies, names, and strengths and weaknesses are presented in Table 6. The main construction types include plug, cutting, seed, pre-grown mat, loose-laid, and modular systems (Design Criteria for Green Roofs, 2020).

Table 6. Green roof construction types

Type of Green Roof	Name	Other Names:	Description Strengths/Weaknesses/Notes	Survival Rate	Installation Labor and Construction Cost	Maintenance Requirement and Cost	Image	Source
Extensive	Plug System	Vegetated systems based on plugs or potted plants, plug-planted systems, plug planting	-Planted in small pots that allow for a controlled and flexible planting arrangement -This system can be added to pre-grown mats or cuttings to increase plant diversity -Variety of plants on green roof -Best used in spring/ autumn to optimize plants in the growing medium - Plant cover can reach up to 80% after a year or two -Accommodates location and expected weather conditions, color, or layout design	High	Medium	Low		(Bauder, 2020; *Design Criteria for Green Roofs*, 2020; Vegetal, 2019)
Extensive	Cutting System	Cutting-based vegetation systems	-It is the spread of small pieces of sedum into the growing medium -It has less control in comparison to plug system -It works for large-scale surface roofs and is the quickest and most economical installation	Medium	Low	Low		(*Design Criteria for Green Roofs*, 2020; Vegetal, 2019)
Extensive	Seed System	Sedum system seeded roofs system, seeding	-It is a distribution of seeds -Limited plants -Soil is bare, so erosion protection is needed -There is less control in comparison to plug system -Lightweight -Can be used over the waterproofing without the need for a secondary layer of substrate	Medium	Low	High		(Bauder, 2020; *Design Criteria for Green Roofs*, 2020)

Type of Green Roof	Name	Other Names:	Description Strengths/Weaknesses/Notes	Survival Rate	Installation Labor and Construction Cost	Maintenance Requirement and Cost	Image	Source
Extensive	Pre-grown Mat System	Sedum mat pre-planted system, continuous modular systems, pre-cultivated vegetation blanket, vegetation mats	-Pre-grown plants on a controlled mat with growing medium -Less control over plant composition and look -Less plant diversity in comparison to plug system, but can be combined with plug system to increase diversity -It consists of a roll grown in an open field, unrolled directly on layers of a system and of growing medium -Mat-based pre-planted vegetated system allows for the fast lay of the system at any time of the season -Require low irrigation -Inability to ventilate the plants -Rolls of growing medium and vegetation -Lightweight option that is simple and fast to install -Instant planting of the roof -If plants are damaged, the whole vegetated mat needs to be replaced -Two options: • XF118 wildflower blanket -a mixture of 24 species of annual and perennial wildflowers • XF300- perennial sedums with some grasses and mosses	Medium	Low-Medium	Medium	 	(Bauder, 2020; *Design Criteria for Green Roofs*, 2020; Tolderlund, 2010; System known as Vegetal, 2019)
Mostly Extensive / Intensive	Modular Tray System	Modular system, hydro pack green roof system, tray system	-Plastic/ metal/ modules/ trays filled with soil or growing medium and supplied to roof pre-grown with mature specimens -Soil may dry out faster since some trays can retain heat, negatively affecting plant health -Lightweight structure -The free-standing nature of the modular components allows easy movement, access and helps repair roof leaks and roof alterations -Sub-categorized into two main modules: rigid material, which is more difficult to be arranged on	Medium-High	Low	Low	 	(Archtoolbox, 2021; Carson et al., 2013; *Design Criteria for Green Roofs*, 2020; Tolderlund, 2010; System known as Vegetal, 2020a)

Type of Green Roof	Name	Other Names:	Description Strengths/Weaknesses/Notes	Survival Rate	Installation Labor and Construction Cost	Maintenance Requirement and Cost	Image	Source
			irregular rooftops but can be grown, pre-planted, and produced off-site; and fabric modules which are more flexible for irregular rooftops but must be grown on-site, on rooftops -Provides a barrier to excessive growth, interlocks the system preventing wind damage, and protects the roof membrane -Simple and fast (easy to change the type of plant, since its modular, the green floor can be lifted for many functions) -Being suitable for both flat and sleep-pitched roofs -Low irrigation consumption due to lack of soil leakage can be an automatic irrigation system connecting pots by a network of pipes, where the water level is controlled at the bottom of the soil by smart valves -Soil is ventilated by pumping air down the pots through dedicated openings without the need to stir the soil					
Extensive	Hybrid System		-Plants and growing media are contained in a tray, once placed on the roof, creating a built-up system with no compartmentalization -Less flexibility in irregular angles -Hard removal	Medium	Low	High		(*Design Criteria for Green Roofs*, 2020)
Extensive / Intensive	Loose Laid System		-Requires high maintenance as the plants tend to need irrigation, pruning, and fertilization -Heavy roof structure -Varying depths of soil in layers of the green roof; between 4-15cm -Typically has a depth of growing medium that exceeds 15-20cm and greater plant diversity -Onsite installation	High	High	High		(Archtoolbox, 2021; Tolderlund, 2010)

Type of Green Roof	Name	Other Names:	Description Strengths/Weaknesses/Notes	Survival Rate	Installation Labor and Construction Cost	Maintenance Requirement and Cost	Image	Source
			-Complex and difficult to change the function -Intensive use loses the ability to ventilate the roots of the plants, and the roof needs to be re-cultivated occasionally.					(Archtoolbox, 2021; Tolderlund, 2010)
Extensive	Biodiverse Habitats	Biodiverse extensive roof	-Encourages a wider spread of birds, insects, and plant species into the area -Replication of the ecological environment of the habitats -Can include different objects such as sand, logs, and rocks, other than just uniform mats or plugs	Medium	Medium	Medium		(Bauder, 2020; *Differnent Types of Green Roof, Sedum Roof,* 2018)
Extensive	Biosolar Roof		-Substrate green roof with a solar photovoltaic array -Mounting system that separates the modules from the substrate to allow for plant growth; ensuring that the maximum height does not block the sunlight from hitting the panels	Medium	Medium	Medium		(Bauder, 2020)

The free-standing nature of the modular tray green roof components allows easy movement throughout and access to the green roof, allowing manageable repair of roof leaks and roof alterations. Modular systems are sub-categorized into two main modules due to material differences. Those rigid materials are more difficult to arrange in irregular rooftops but can be grown and produced off-site. The overall characteristics and flexibility of rigid modular tray systems make them suitable for developed and existing buildings. In comparison, fabric modules are more flexible for irregular rooftops but must be grown on-site on rooftops. This can be challenging to implement on the existing building due to labor, installation, cost, and other varying limitations. In addition, the pre-grown mats system works similarly but is composed and arranged of rolls of growing medium and vegetation (Tolderlund, 2010). It provides immediate plant coverage with low maintenance and easy installation.

On the flip side, the pre-grown mat system is extremely limited in plant composition and look. Due to its singular roll-grown system over an open field, it has the least control over plant variety and depth. This makes it an easily repetitive and unvaried roof system implemented over different buildings. The level of control to easily maintain and directly improve plants is even more efficient in modular tray systems compared to loose-laid, plug, and cutting systems due to their construction methods (Design Criteria for Green Roofs, 2020).

From the above-mentioned extensive construction types outlined in Table 6, the modular tray system is considered the most convenient maintenance system because one plant can be altered without needing to change the entire system (Archtoolbox, 2021). This is due to its high level of control over individual plant trays. While it can be argued that maintaining functional 10cm shallow extensive green roofs is a challenge, the strengths of using modular tray systems for Qatar's hot arid climate include low weight, low capital investment, low maintenance of plants, limited roof leaks and alterations, low irrigation, easy replacements, and high suitability for large projects (Tolderlund, 2010). Overall, the modular tray system is strategic as they are flexible and can be monitored under desired conditions and factors due to its self-contained, free-standing nature, arrangement, and installation (Srivastava, 2011). Furthermore, a modular roof system is the most suitable due to four influential factors. Firstly, quick greening for a specific area. Second, the need for plants of a particular size. Thirdly, avoiding technical problems related to water leakage as a result of poor moisture insulation implementation in roof covering with soil. And fourthly, the possibility of the use of plants to cover the entire roof surface in summer, such as using soil coverings and decaying plants, and parts of it were exposed in the winter by moving or gathering plants during the winter season to prevent unwanted shades.

The modular system has been previously researched and tested in Qatar's hot arid climate as part of the "Biofacades" green wall NPRP 7-1406-2-507 research project at Qatar University (Figure 14). The system is inclusive of water channels, plastic barriers, a planter liner (geotextile-wicking material – fabric is porous "air-pruning" which prevents roots from getting saturated, strong and fibrous root system develops, more absorption of nutrients, greater resistance to harsh weather conditions, disease and pests, and higher yields), and plant species (Fadli et al., 2018).

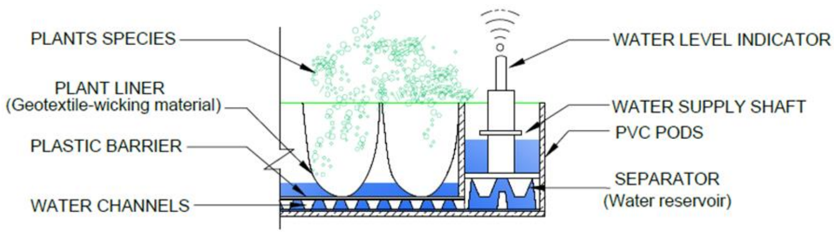


Figure 14. Biofacade construction detail (Source: Fadli, Bahrami, & Zaina, 2018).

In addition, unlike the vegetated mat, which requires a drainage course to avoid surface flow and substrate erosion, the walls of the modular tray system limit surface runoff. At the same time, the base provides corrugated air space for drainage. Thus, the modular system can be installed immediately on the structure of the roof waterproof membrane (Carson et al., 2013). The system can also be designed with a water reservoir for irrigation purposes and needs little to no additions to the existing roof of the building (Cahill et al., 2007; Vegetal, 2020a). Lastly, fertilizers are required only when weeds need to be controlled (Archtoolbox, 2021). This level of control, manipulation, and instant roof cover suit the climate conditions, making it advantageous for Qatar. Thus, the strengths of the modular system present a reasonable choice for Qatar’s hot arid climate and offer an instant cover for the roof structure.

1.3.2.3 Plants and Growing Medium

This section addresses the limiting factors, selection, assessment criteria, and growing medium (soil) of the green roof plant's performance for implementation in Qatar’s climate (Figure 15). The limiting factors that can affect implementation associated with SGR plants include irrigation and building load restrictions. Upon viewing the restricting circumstances of utilizing roofs, other factors of plant selection also need consideration, such as growth rates, availability, drought resistance, and durability. Lastly, the growing medium properties, components, and growing depths of different substrates that affect green roofs and plant performance are presented.

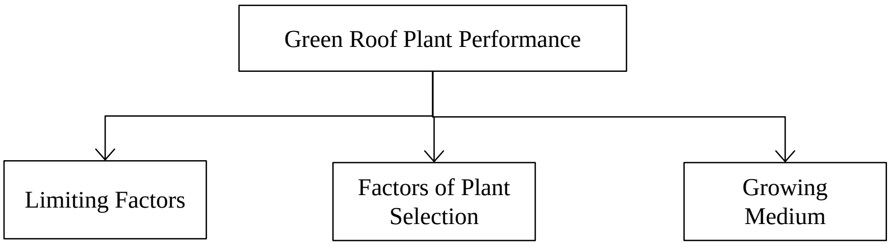


Figure 15. Plants design considerations of a green roof (Adapted from: Bauder, 2019; Alberta, 2020; Dunnett & Kingsbury, 2008; Tolderlund, 2010; Fadli, Bahrami, & Zaina, 2018; Zaina & Fadli, 2020; Kotsiris et al., 2013; Palla et al., 2009; Cao et al., 2014; Vijayaraghavan & Joshi, 2014; Gabrych et al., 2016; Bisceglie et al., 2014; Ondoño et al., 2014; Xiao et al., 2014; Saeid, 2013).

It is important to highlight that the natural setting for plant growth is not on roofs (Shafique et al., 2018). Irrigation and building load restrictions are limiting factors for the plant rooftop environments. Implementation of an irrigation system can be complex, require regular maintenance, and be constrictive due to the roof slope and water source. A building’s load limitations and confinements restrict the soil media depth, consisting of vital nutrients to sustain a plant’s performance (Figure 16).

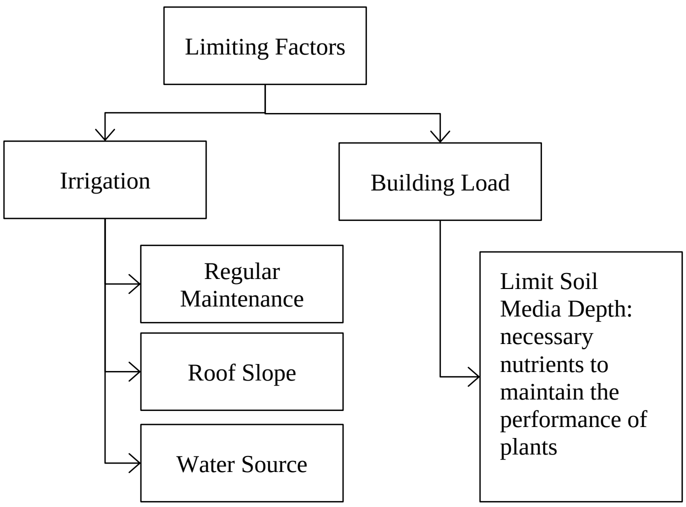


Figure 16. Limiting factors of green roof plants (Adapted from: Shafique et al., 2018).

Figure 17 summarizes the essential factors for plant selections from multiple literatures (Alberta, 2020; Bauder, 2019; Dunnett & Kingsbury, 2008; Shafique et al., 2018; Tolderlund, 2010; Zaina & Fadli, 2020). Alberta (2020) confirms that plants must be selected according to the building's location and orientation, where wind, sun, shading, and rainfall directly affect the plant's survival. Besides, despite the challenges that arise, Shafique et al. (2018) present a methodology to quantify these factors for optimal vegetation choice. Considering the hot arid region of Doha, analyzing these factors assists in choosing the most suitable plants for an SGR installation.

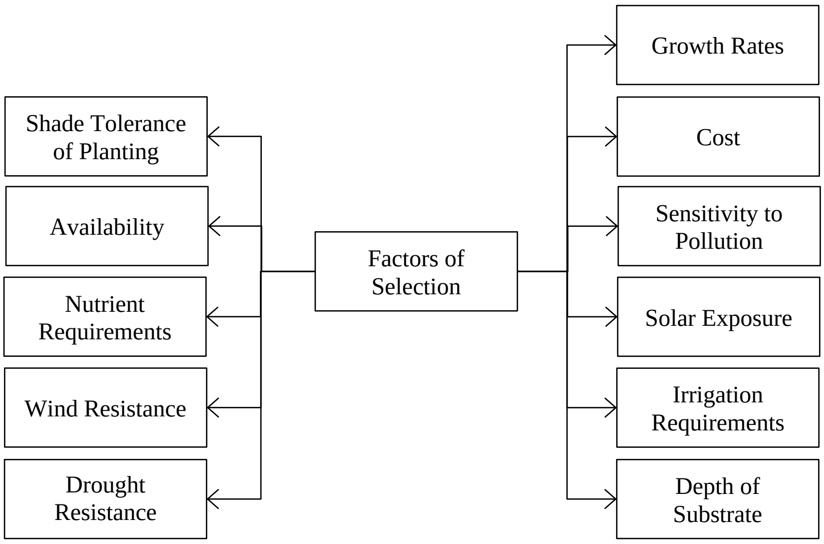


Figure 17. Factors of plant selection of a green roof (Adapted from: Bauder, 2019; Shafique et al., 2018; Dunnett & Kingsbury, 2008; Tolderlund, 2010; Zaina & Fadli, 2020).

Furthermore, a plant database must be developed in a hot, arid climate to understand urban foliage for rooftop gardening better. These plants must be able to withstand extended sunlight exposure on rooftops. In hot arid zones, energy savings of up to 80% have been credited by carefully planting and placing vegetation on buildings.

However, the evidence of such studies showing the positive outcomes of certain plants, particularly trees, on diminishing a building's energy consumption remains circumstantial. In addition, the assets and processes of a building determine the actual amount of potential energy saved (Erell et al., 2011). Table 7 demonstrates a few sets of data regarding the plants and their characteristics for hot and arid climates, which, at the moment, are comparable to roughly 200 types of crops, trees, grasses, and shrubs (Henninger et al., 2015). This table lists the watering conditions needed for the specific type of plants and the light and thermal conditions it exhibits, thereby allowing a thorough and appropriate selection towards integrating an SGR in Qatar.

It is also critical to highlight that the mentioned plants in Table 7 fall under plant type categories. These categories include annuals, herbaceous perennials, hardy succulents, grasses, herbs, evergreen plants, accent plants, ground cover, and native plants, presented in Figure 18 (Bousselot et al., 2011; Dahlqvist, 2010; Dunnett & Kingsbury, 2008; Emilsson, 2008; Hawke, 2015; Milberger Gardening, 2022; Nagase & Dunnett, 2010; Rowe & Getter, 2015). Understanding and exploring the myriad plant types are essential as they help grasp a more thorough comprehension of plant selection on the SGR in Qatar's hot and arid climate.

Table 7. Vegetation types suitable for green roofs in hot arid regions (Adapted from: Henninger et al., 2015; Texas Native Plants Database, 2019; Crocus, 2020; Vijayaraghavan & Joshi, 2014; Schweitzer & Erell, 2014; Cordifolia, 2020; Fern, 2019; Saeid, 2013; Flora of Qatar, 2016; Floridata Home, 2020; Plantz Africa, 2018; Andrews, 2021; Angus, 2020; Fine Gardening, 2021; Plant Finder, 2020)

Scientific name	Description	Watering conditions	Light & thermal conditions
Aptenia Cordifolia (Haialam) 	*- Ground-covering herb - Height: 7-10cm; can climb on adjacent plant - Flowers: • Small bright pink flowers in spring and summer • May blossom throughout the year - Leaves: 1-3cm long, heart-shaped, flat, petiolate, dark green, free, glossy, minutely papillate*	*- Drought tolerant - With ample water availability, it overwhelms all adjacent plants, climbing on any structure in its path - Can survive in summer without irrigation and later thrive during the rainy-wet season - Although always wet soil can cause it to rot*	*- Exposure: full sun or semi-shade - Tolerates high temperature*
Euphorbia Millbig 	*- Plant is an annual, biennial, or perennial herbs, woody shrubs - Roots are thick or fine and tuberous or fleshy - Flower color: deep purple or reddish and white - Height: 15–90cm*	*- Drought and heat tolerant - Low maintenance - Good drainage - Prefers more moisture than other types of plants*	*- Exposure: full sun or semi-shade*
Sesuvium Portulacastrum 	*- Leaves: thick and fleshy leaves on succulent, greenish-red stems that branch, creating dense stands near ground level - Perennials - ground cover - Flower color: small, showy pink, purple and white flowers; each flower opens for a few hours/day - Height: 15-30cm - Foliage: smooth and shiny/ glossy texture - Soil: not well-drained*	*- Resident to drought - Watering during drought is required - Grow very happily in moist or wet conditions - Average water requirements, water regularly, and not over watering*	*- Prefers a full sun position - Withstands heat and wind conditions*
Agave Americana 	*- Types of agave include blue, green, grey, rainbow, salmiana, and thorny agave - Hardy succulents (evergreen), along with sharp leaves, appropriate for poor and dry soils - Height: 8-9m - Spread: 1.8-3m*	*- Resident to drought in hot arid climates - Water potential: high in sandy than in rocky soils, and root growth is greatest in sandy soils - Needs a dry environment and good drainage*	*- Prefers a full sun position*

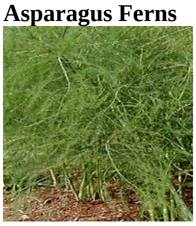
Scientific name	Description	Watering conditions	Light & thermal conditions
Aloe Vera 	*- Height: 60-90cm - Leaves: green, gray leaves assembled in a shaped rosette - Height: grow up to 45.7cm - Spread: 5.1cm at base - Easily grows in a gravelly or sandy, well-drained soil - Hardy succulents*	*- Drought resident in hot arid climates - Needs a dry environment and good drainage*	*- Exposure: full sun - Withstands high temperature and reduces sun radiation*
Asparagus Ferns 	*- Leaves are decreased to small spines on the stems - Evergreen perennial - Height: 150-250cm - Spread: 60 to 80cm - Flower color: green - Foliage color: light green*	*- Performs best with regular watering; however, allow the soil to dry out - Withstands acid and droughty soil - Needs well-drained soil*	*- Best in partial shade and full sun*
Tradescantia Pallida 	*- Herbaceous perennials - Plants have violet-purple stems and leaves and produce three-petalled blooms of white and pink from early summer to winter - Requires low maintenance - Height: 15-25cm - Spread: 30-45cm*	*- Drought tolerant - Water requirements (medium)*	*- Full sun to partial shade*
Eremophila Maculata 	*- Low-spreading shrub - Flower color: often varies and may be pink, mauve, red, orange, or yellow - Small shrub - Ground cover (plant usage) - Evergreen, mounted-shaped (growth habit) - Perennial (lifespan) - Height: 1-2m - Spread: 2-3m*	*- Drought tolerant - Minimal supplementary watering - Low maintenance - Soil moisture: dry, well-drained*	*- Full sun to partial light shade*
Ruellia Brittoniana 	*- Shrubby perennial (ground covers) boasting a profusion of petunia-like, vibrant lavender-blue flowers - Glossy green leaves - Height: 60-90cm - Spread: 30-60cm*	*Tolerance: deer, drought, medium-wet soil - Moist but well-drained - Low maintenance - Water needs: low, average, and high*	*- Full sun to partial shade*
Pennisetum Setaceum 'Rubrum' 	*- Mainly ornamental grass and known as fountain grass - Deciduous/ evergreen: herbaceous - Height: 90-150cm - Spread: 60-120cm rounded mounds - Color: green or red*	*- Drought tolerant - Low maintenance - Moderately fertile - Well-drained soils - Low to average water requirement*	*- Full sun in light*

Figure 18. Taxonomy of plant types (Adapted from: Bousselot et al., 2011; Dahlqvist, 2010; Dunnett & Kingsbury, 2008; Emilsson, 2008; Hawke, 2015; Milberger Gardening, 2022; Nagase & Dunnett, 2010; Rowe & Getter, 2015).

When selecting plants, consideration must be taken on whether plants are a year-round visual interest. Hardy succulents like Sempervivum, sedum, and Jovibarba have textured foliage. They are mostly evergreen colored, making them aesthetically and visually needed, while herbaceous perennials lose their leaves during winter and have a restricted flowering period. Annuals can be self-sawing after their first year, but they dispersed at random on the roof. To maintain a continuous year-round interest, it is suggested to utilize a combination of hardy succulents, annuals, and herbaceous perennials (Dunnett & Kingsbury, 2008). Ground cover plants with limited accent plants are best recommended for green roofs (Hawke, 2015).

Moreover, the characteristics of native plants include adapting to climatic and ecological conditions, resisting plant diseases and insect damage, and producing stable biodiversity, making them suitable for green roofs (Rowe & Getter, 2015). Schweitzer and Erell's (2014) study shows that the best native plant species for dryer settings would be the Aptenia Cordi Folia. More studies on the selected native plant species for green roofs is required. In turn, the water quality and ecosystem enhancements are relative to plant species selection (Shafique et al., 2018).

In Qatar, water resources are scarce. This lack limits the plant selection for green rooftops. Plants must have the ability to survive with a minimal nutrient supply (Takebayashi & Moriyama, 2007). Therefore, the type of garden plants will categorically differ from those on the rooftop. Thus, the planting option is a limiting factor for green roofs in this hot arid region, and it is essential to find the plant type that endure longer with minimal irrigation. Durhman et al. (2006) stated that the sedum species could survive active photosynthetic metabolism without water, lasting more than four months. Comparatively, Terri et al. (1986) portrayed the sedum rubrotinctum ability to survive without irrigation for two years.

The study conducted by Berardi et al. (2014) further analyzed different types of plants, including Pennisetum, Sesuvium, Aptenia, and Halimione, and observed that Pennisetum is the most significant. In agreement, based on an experimental study, Fadli et al. (2018) confirmed that the most important types of plants in a hot arid region include Pennisetum Rubrum and Asparagus Ferns, Sessivium Portulacastrum, Rheo Spathacea, Tradescantia Pallida, and Aloe Vera.

Most of the plants selected for Qatar comprise a standard mix as a base for the SGR, as shown in Table 8. A standard plant mix is an ideal lightweight solution for a non-accessible roof structure compared to accent mix and custom mix. Moreover, these plants are suitable for waterproofing assemblies, decking types, pitch, and partial to full sun exposure. In addition, the common plant types in a standard mix are the most suitable for Qatar’s hot and arid climate as it consists of Sedum, Perennial, and Herbaceous plants, most of which are native plants that can resist drought.

Table 8. Standard plant mix - plant varieties (Adapted from: System known as Vegetal, 2015)

Standard Mix	Accent Mix	Custom Mix
		
- Consists of numerous varieties of Sedums and Aromatic, Perennial, and Herbaceous plants - The mix needs minimal everyday maintenance and a 10-day lead time to arrange	- Accent mix has the same base plants as the Standard Mix but with 1-2 plugs of accent plants in each module to easily improve the visual appearance - Requires an average of 6 weeks lead time to order	- The custom mix features a flexible variety of plant species - Plant mix can feed the visual requirements of any green roof project

Overall, in Qatar’s hot arid region, it is more convenient to use native plant species that are easy to access, available, consume little water, and can remain without water for an extended period. Native plant types also have other advantages, including withstanding extended sunlight exposure, requiring minimal cost, and ease of transportation. Furthermore, it is crucial to select mainly hardy species for SGRs. Sedum, Sesuvium, Asparagus Ferns, and Tradescantia Pallida are succulent and ground cover plants that are highly resistant to the multiple sources of stress related to the roof structure's living conditions. These plant types can create long-lasting plant cover and tolerate long dry periods for continued growth as they have already adapted to Qatar's region's thermal and watering conditions.

An optimum selection must be made for the growth medium (soil), as this layer will affect a plant’s flourishment and, ultimately, the green roof's success. The perfect media for plantations must possess certain properties, as illustrated in Figure 19. These characteristics lead to water quality enhancements and result in a synergy between organic minerals, ultimately causing a plant to nourish and flourish. Local settings must also be taken into consideration and, as such, determine which substrate would be best to support the plants (Fadli et al., 2018).

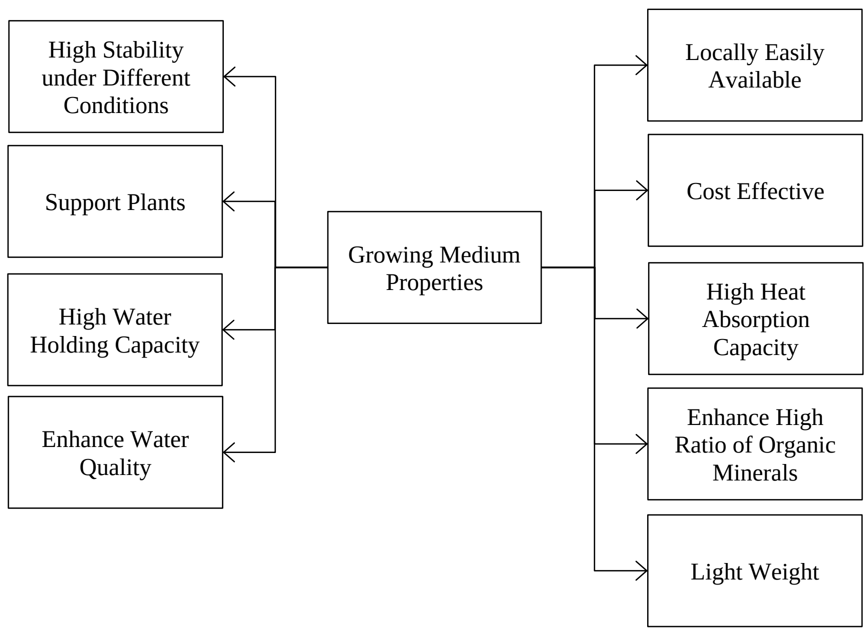


Figure 19. Growing medium properties of a green roof (Redrafted from: Fadli, Bahrami, & Zaina, 2018).

Many studies showed that commercial substrate was used for green roofs, whereas a smaller amount of substrate is recommended to induce cost-effective and lightweight materials with several advantages (Gabrych et al., 2016; Vijayaraghavan & Joshi, 2014; Vijayaraghavan & Raja, 2015). The numerous components in the substrate can comprise zeolite, pumice, scoria, perlite, vermicaulite, crushed brick, peat, and other low-cost waste materials (Palla et al., 2009; Kotsiris et al., 2013; Bisceglie et al., 2014; Cao et al., 20 14; Xiao et al., 2014). Some research has also implied that utilizing 80% inorganic materials for the growing media will reduce the weight of green roofs

(Landschaftsbau, 2002; Vijayaraghavan, 2016). Growing media performance can be improved by having a high absorption capability while maintaining less leaching. Organic constituents are recommended in the substrate to supply green roofs with the required nutrients (Kotsiris et al., 2013; Nagase & Dunnett, 2011). Table 9 displays the variety of reliable plants for a hot and arid climate in various growing mediums based on different literature (Fern, 2019; Henninger et al., 2015; *Native Plants Hawaii*, 2009; *Texas Native Plants Database*, 2019; Saeid, 2013).

Table 9. Plant types that are reliable in hot and arid climates in the different growing mediums (Redrafted from: Fern, 2019; Henninger et al., 2015; Saeid, 2013)

Growing Medium	**Description**	**Suitable Plant Types**	
0-5cm	- Shallow varieties of roots that survive in dry and humid environments - Can survive for 2-3 weeks with no irrigation - Flowers and leaves come in a variety of colors - Matures at different times of the year	 1. Sedum (stone crop)	 2. Delosperma (ice plant)
5-10cm	Deeper soil - wider varieties of plantings that are drought resistant	 1. Grasses	 2. Alliums
		 3. Herbs	 4. Wildflowers
		 5. Perennials	 6. Alpines

Growing Medium	Description	Suitable Plant Types
10-15cm	A much larger variety of plants can be utilized	 1. Grasses  2. Columbines  3. Asters  4. Black-eyed Susan  5. Bulbs  6. Wildflowers  7. Hardy Sub-Shrubs  8. Annuals

1.3.3 Smart Green Roof Systems

A smart building is any structure that uses automated systems to allow the inclusion of intelligence in buildings and the centralization and sharing of multiple buildings over a shared network (Zanella et al., 2014). This smart interconnection of these building features, such as air conditioning, lighting, elevators, energy systems, and water systems, allows the control of the buildings automatically as well as internet monitoring of the building functions (Baig et al., 2017). This smart framework can be enabled in green roofs to enhance the roof's performance sustainably. A classification of the irrigation methods, such as conventional and smart irrigation systems (SIS), and an analysis of the different types of SIS, such as weather-based and soil-based systems, are discussed for the climatic context of Qatar in 1.3.3.1. The next sub-section 1.3.3.2 delves into a review of case studies and recent trends of the SGR systems in hot arid climates. Selected data has been analyzed to deduce innovative outcomes based on systematic literature review, decision support system, and morphological thinking for SIS which is presented in 1.3.3.3. This analysis is crucial for developing an inventive SGR since it parametrizes the problem space by going through cycles of synthesis and analysis on the collected data. The objective behind this section is to understand SGR systems and develop recommendations for optimal, smart, effective, accessible and advanced technology solutions to achieve a SGR in hot arid regions.

1.3.3.1 Manual and Smart Irrigation Systems

In specific to water efficiency and saving practices, the method of irrigation supplied to green roof plants through an integrated smart technology preserves vastly more water than the conventional irrigation technique. This section will discuss the conventional and smart irrigation types and elaborate on how smart irrigation technology accurately supplies appropriate watering to plants based on weather and soil data.

To begin with, there are two categories of irrigation types, conventional and smart irrigation systems (Figure 20). The adopted irrigation technique directly affects the water absorption pattern, evaporation rate, infiltration rate, nutrients, and deep percolation of the soil. Conventional surface irrigation techniques such as manual, flooding, and furrow watering are the oldest and most practiced worldwide (Abioye et al., 2020). These methods lead to potential water loss and low saving capacity (Gillies, 2017). It is characterized by extreme water supply needs for plant survival, increasing the leaching process, decreasing soil nutrient levels, and reducing crop yield (Adamala et al., 2014). Hence, by implementing smart water-saving techniques and control-monitoring strategies through precision irrigation, the conventional surface method could be improved (Gillies, 2010).

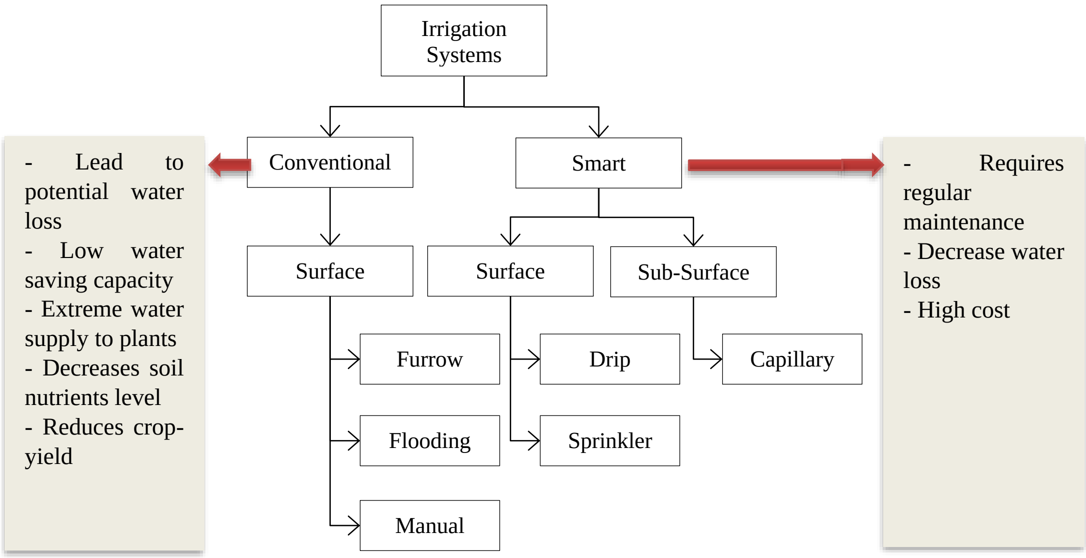


Figure 20. Conventional and smart irrigation systems; their advantages and disadvantages (Adapted from: Abioye et al., 2020; Gillies, 2017; Semananda et al., 2018).

Smart water-saving strategies include surface, drip or sprinkler, and sub-surface capillary irrigation. Table 10 presents the different types of irrigation delivery methods for green roofs. Drip irrigation decreases the water loss rate, resulting from evaporation affected by surface runoff and wind (Rekha & Jaydeva, 2015). Hou and colleagues (2015) justify that carefully manipulating the space between the drippers is crucial to prevent substantial water loss.

Table 10. Types of irrigation delivery methods for green roofs (Adapted from: Irrigation | Growing Green Guide, 2014)

Delivery method	Advantages	Disadvantages
Micro spray	- Visible - Reliable - Low cost - Easy to install	- High amounts of water loss due to wind and evaporation - Foliage wetting of potential increased disease - Uneven allocation of plant interception
Surface drippers/perforated pipes	- Visible - Low cost - Even distribution of water	- Loss of water
Sub-surface drippers/ perforated pipes	- Low cost - Reasonable productivity (water distribution to the root)	- Nonvisible, thus, maintenance and repair are hard, laid below the soil surface - High chance for damage caused by people digging
Sub-surface capillary	- High productivity	- Nonvisible, thus, maintenance and repair are hard - High cost - Water will not reach plants if 'capillary rise' of the substrate is not placed
Wicking is associated with irrigation in the drainage layer	- High productivity - Easy to install	- Connected to exclusive systems, - Water will not reach plants if 'capillary rise' of the substrate is not placed
Hose	- Valid for residential application for easily accessed areas - Permits monitoring to occur simultaneously	- Cost (requires a person on-site) - Low water productivity - Distribution is uneven - Foliage wetting

Many study investigations conclude that the smart sub-surface capillary wicking irrigation method offers better yield output and higher water-saving capabilities than other surface irrigation types (Abidin et al., 2014; Ohaba et al., 2015; Zaina, Fadli, & Khamidi, 2021). Alternatively, Fujimaki and Mamedov (2018) have observed that the water's upward motion through capillary irrigation can collect soil salts. Therefore, increasing the soil's salinity of the plant can only be decreased when soil begins to leach water.

To guarantee that a plant remains healthy during long periods of drought, constant and sufficient water levels must be maintained. Through the work of Bauder (2019), the implementation of an automatic irrigation system ensures this. Selecting an SIS will depend on multiple variables, such as the building, roof function and type, water availability, technical circumstances, local climatic settings, plants, and soil or growing media, as presented in Figure 21.

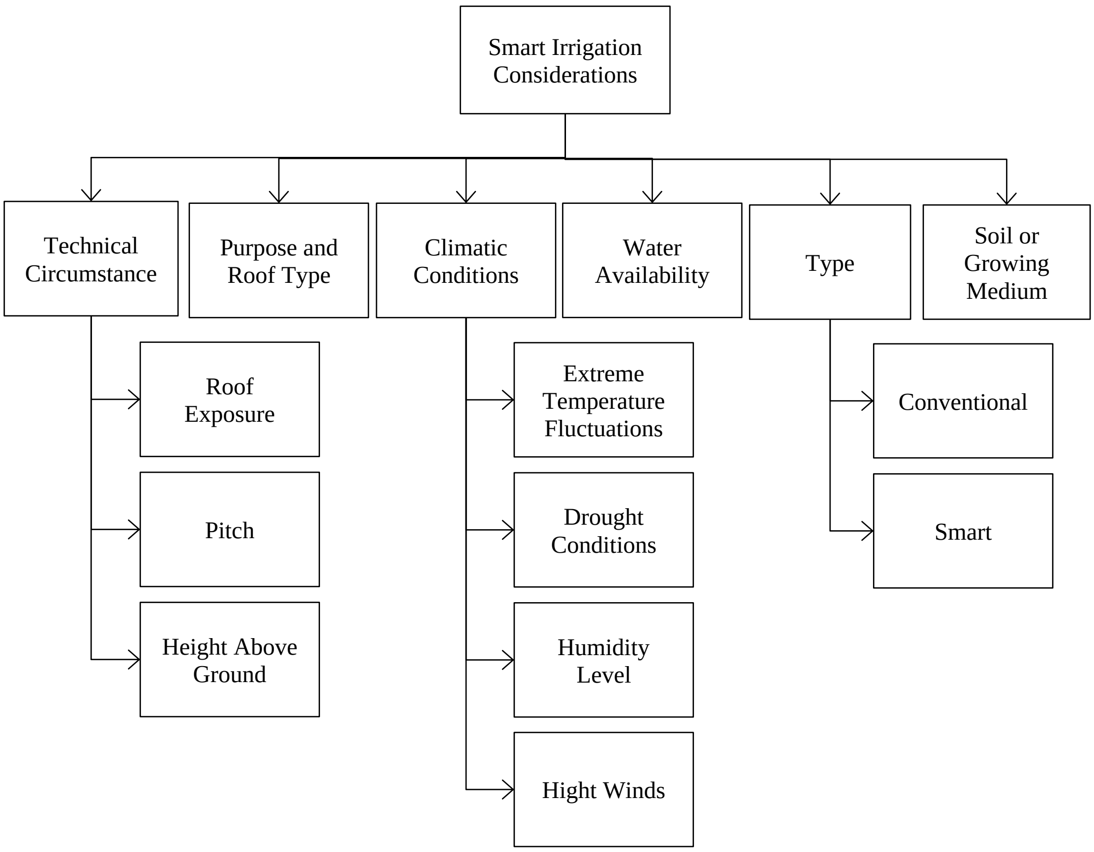


Figure 21. Smart irrigation system design considerations (Adapted from: Amorim & Mendonça, 2017; System known as Vegetal, 2018).

The decision to use SGR systems over manual plant irrigation systems will be grounded on the plants' needs and growing medium features, further depicted in Figure 20. In the case of intensive green roofs with highly layered growing medium substrate, more irrigation is required, as shown in Table 11. While with the extensive green roofs shallow growing medium, only temporary and low irrigation is needed, limiting specific plant types (Zaina & Fadli, 2020). If the growing medium of the green roof limits the lateral water movement, drip irrigation will most likely be inadequate. At times, it is necessary to have custom detailed irrigation systems to reduce the damage caused to the waterproofing membrane due to the lower depths of the growing medium. At other times, drip irrigation may seem more valuable if it is placed under the plant layer to refrain from heating the drip line and irrigating the roots. On the other hand, with shallower applications in depth, spray irrigation must be regarded in place of drip irrigation as it will spray more laterally when used over a faster draining medium.

Table 11. Types of green roofs and irrigation capacity with associate limitations (Adapted from: Ohaba et al., 2015; Zaina & Fadli, 2020)

Type of green roof	Irrigation	Limitations
Extensive	Low irrigation: temporary type of watering	Limited to the formation of sedum species
Intensive	More irrigation: small spray-heads – drip irrigation	Reliant on the layer of soil

Numerous publications claim that the drip irrigation system uses sensor data to determine the water quantity that is required, conserving water and reducing soil erosion (Chaware et al., 2015; Dubey & Dubey, 2018; García et al., 2020; Ghodake & Mulani, 2016; Schuch, 2006). According to literature, the most adaptable and efficient SGR irrigation method for irrigation precision is the drip irrigation system when used correctly (García et al., 2020; Hamami & Nassereddine, 2020). The timing for drip irrigation depends on the plant type chosen and the hot arid condition. Moreover, it is crucial to consider the plant types that are used as the green plantations are horizontal additions to existing building structures in Qatar. SGRs with easy-to-install systems and more shallow plant types are more strategic for use. This decreases the demand for additions or modifications to existing roof buildings and refrains from blocking the building structure. A further environmentally, economically, and socially beneficial approach is enabling the transition to renewable solar-powered SIS with battery-free smart irrigation, where valves, soil sensors, and system controls are powered by small solar cells. It prevents pollution, uses less energy, and has lower operating and maintenance expenses. Hence, a well-organized drip irrigation SGR control system is required to improvise the mentioned irrigation methods and their limitations, as outlined in Table 11, through real-time monitoring and control (Fadli et al., 2019; Fadli & Alsaeed, 2020; Fujimaki & Mamedov, 2018).

To achieve enhanced irrigation accuracy, smart technology monitoring and control utilizes weather-based and soil-based data (Singh et al., 2018). To implement on-site weather-based technology, the weather data sensors are small and can be easily mounted on any building, fence, or object with an available wireless connection between the sensor and controller. They are also relatively affordable with easy installation, making them suitable for most applications, including residential and low-rise office buildings. Research shows the benefits of 20-25% water savings reaped from weather-based sensors that easily overcome the price point of installation. This is due to the computing power of the controller that inputs information regarding plant type, soil type, sprinkler type, exposure, and slope. The National Association of Landscape Professionals (2021) reported up to 40% savings on water consumption when using weather-based controllers compared to manual irrigation methods. Data also shows that integrated weather-based technology is more accurate than only add-on controllers due to the additional weather site information collected (National Association of Landscape Professionals, 2021).

In comparison, soil-based technology uses on-site sensors to measure the soil's moisture content. This data is used to adjust the time of water irrigation for the plants. There are two types of soil-based systems: suspended-cycle and water-on-demand irrigation (National Association of Landscape Professionals, 2021). To implement, suspended-cycle irrigation sensors can be added to existing controllers. In contrast, water-on-demand irrigation is more difficult as it requires a new controller with sensors (National Association of Landscape Professionals, 2021). A centralized irrigation communication portal developed by Montoro et al. (2011) sends and provides user recommendations via email or SMS to notify of the changes in soil or climatic conditions (Figure 22).

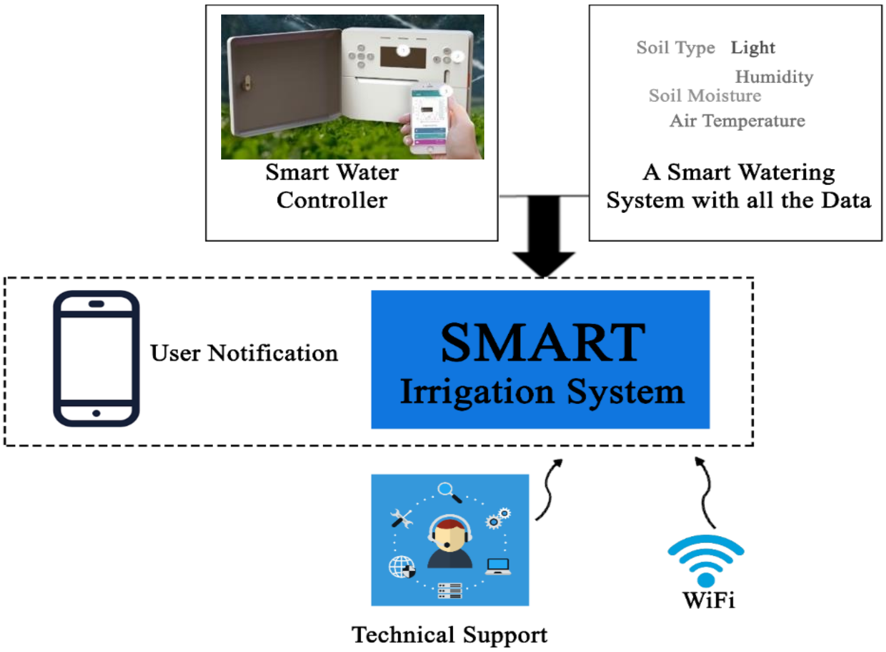


Figure 22. Smart irrigation system set-up.

Due to the inherent accuracy of measuring soil moisture to determine plants' watering needs, a soil-based smart technology system instead of a weather-based system is more suitable for this experiment. In addition, water-on-demand soil moisture-based irrigation automatically adjusts the watering schedule according to the plant's demands, effectively irrigating plants and reducing water wastage. This efficient smart irrigation watering practice thus meets the aim of designing, developing, and implementing an SGR system.

1.3.3.2 Smart Systems

This section will first highlight the most relevant case studies of irrigation management for SGRs. Case studies and trends of different smart technologies and irrigation systems, as well as their implementations within the literature, will be explored to propose sustainable, smart, and innovative irrigation system recommendations for green roofs in hot arid climates such as Qatar. To further optimize and enhance smart irrigation type benefits, smart technology means such as wireless sensor networks (WSN) and Internet of Things (IoT) will be introduced.

WSN and IoT adaptations to implement a smart irrigation technique is necessary for precision water supply and distribution. On the one hand, WSN gathers real-time data and sends it to a primary server in the control center using a wireless link. This generates a command to control the water flow. Thus, enhancing the effectiveness of water supply and distribution. Alternatively, the IoT is a smart computing device that allows sending and receiving relevant data. Wireless connectivity and data transfer increase smart irrigation management systems' productivity. Their standard application and increased advantages have been studied and swiftly incorporated into workflows, projecting an IoT agricultural sector price of $30 billion by 2023 (Digiteum, 2019).

Casadesús et al. (2012) and Todorovic et al. (2016) propose an affordable cloud-based irrigation scheduling application that consumes less water than drip irrigation and automatically schedules irrigation in real-time based on a soil-water measurement. To enhance the real-time decision-making process, the IoT cloud platform can be accessed remotely by the user via fixed devices or smartphones (Jayaraman et al., 2016; Pongnumkul et al., 2015). As a result, users will find it easier to monitor climatic conditions, soil, and plants, which improves the effectiveness of precision irrigation and the growth of plants Innovative irrigation control methods aim to optimize fertilizer use, increase plant growth and production, and maximize water use efficiency (Boman et al., 2015). As a result of improved irrigation performance, there is a refinement in solar radiation, relative humidity, air temperature, and rainfall (Marinescu et al., 2017).

The literature review studies conducted for green roof smart technologies have shown that current smart green systems have been emerging, including IoT systems, fuzzy logic, artificial intelligence, and, machine learning as presented in Table 12 (Al-Ali et al., 2020; Casadesus et al., 2012; Dursun & Ozden, 2011; Goap et al., 2018; Jaguey et al., 2015; Katyara et al., 2017; Kim et al., 2008; Krishnan et al., 2020; Kumar & Kusuma, 2016; Liao et al., 2021; Mirás-Avalos et al., 2019; Montoro et al., 2011; Olberz et al., 2018; Podder et al., 2021; Roopaei et al., 2017; Shaker & Imran, 2013; Tiglao et al., 2020; Todorovic et al., 2016; Zhao et al., 2018). Whether in agriculture or greenhouses, these innovations show the tremendous advantages and importance such additions can bring to the community, urban life, culture, and environment.

Table 12. Literature review of smart irrigation systems

References	Green roof	Smart/IoT/ Technology	Irrigation Scheduling	Irrigation System	Plant Types	Plant growth monitoring	Cost	Climatic conditions	Name of SIS	Generic Description	Instruments/ Data
(Montoro et al., 2011)	Horizontal (farm)	SMS messages, email, web-based	Weekly manual irrigation based on PD, ID, and rainfall	Sprinkler	Crops, cereals	NI	Low	Hot semiarid in Albacete, Central Spain	ISS-ITAP	-Real-time climatic data acquisition	No information
(Casadesús et al., 2012)	Horizontal (field)	Web-based	Automated daily irrigation based on climate, and PD	Drip	Trees, fruits, vegetables	Monitoring the plants' water stress and the crop	Cost-effective	Catalonia, Spain	IRRIX	Real-time climatic data acquisition	-Solenoid valve -Digital water meter (CZ2000-3M) -Standalone irrigation controller (Agronic 4000) -Soil water sensors (EC-20)
(Todorovic et al., 2016)	Horizontal	Web-based, smart devices	Automatic irrigation based on SW	Sprinkler/ drippers spacing and discharge	Fruits, vegetables	Sensor-based monitoring of soil, plant, atmosphere	Cost-effective	Apulia Region, Italy	Hydro-Tech	-Crop-soil water balance -Real-time climate data	Crop evapotranspiration, weather data, crop transpiration, soil evaporation, soil water balance, SM stress, the volume of irrigation
(Mirás-Avalos et al., 2019)	Horizontal (field)	NI	Proposal of scheduling based on volume, time of watering, soil evaporation, crop transpiration	Drip	Crops	SW, crop height & coverage	NI	Semi-arid Mediterranean in Southeast Spain	IA	Calculation of a soil water balance in the root zone	Soil water content (EC-10)
(Dursun & Ozden, 2011)	Horizontal (field)	UFM-M11 wireless module, micro-controller chip, remote control	Automation technology, such as solar power	Drip	Cherry trees	Monitoring of SM at different growth stages	Low	Semi-arid region in Turkey, central Anatolia	Drip irrigation automation system	Wireless app. supported by SM sensors & real-time monitoring of SW	Soil moisture 10SH sensor
(Zhao et al., 2018)	Horizontal (field)	URI and VRI	Irrigation scheduling based on soil moisture sensors	-No information -Application of Nitrogen, potassium fertilizers	Winter wheat and summer maize	NI	Low	Arid and Humid China	VRI and URI	Utilizing a WSN and soil moisture sensors, auto irrigation	Decagon soil moisture sensors EM50, decagon data loggers 5TE for soil moisture and soil water content

References	Green roof	Smart/IoT/ Technology	Irrigation Scheduling	Irrigation System	Plant Types	Plant growth monitoring	Cost	Climatic conditions	Name of SIS	Generic Description	Instruments/ Data
(Shaker & Imran, 2013)	Horizontal (greenhouse)	Amega382P microcontroller XBee, ZigBee, LCD screen	NI	No information	Any crops at any time of the year	NI	Low	NI	WSN with smart irrigation technique	Monitoring greenhouse microclimate based on WSN	DHT-22 and EC-5 to measure humidity, temperature, soil water content, soil moisture
(Katyara et al., 2017)	Horizontal (field)	Computer-based	NI	Ground water storage	Rice Canal	NI	Cost-effective	Pakistan	WSN and SCADA	Smart & remote monitoring of the irrigation system	Soil moisture, temperature, humidity sensor, solar panel, SCADA monitoring center
(Krishnan et al., 2020)	Horizontal (field)	Mobile tech., web-based	Fuzzy logic controller to compute (SM, temperature, and humidity)	Drip	NI	NI	Cost-effective	All-weather conditions	Fuzzy Logic using IoT	System provides soil humidity & temperature	Arduino controller, GSM, motor, plant leaf image SM sensor, DHT-11 sensor
(Al-Ali et al., 2020)	Horizontal	WiFi, solar power, and two types of control modes (local and mobile)	Fuzzy logic-based control mode (depending on sensor readings, turn on or off the water pumps)	Drip	NI	NI	Cost-effective	All-weather conditions	IoT-solar energy smart irrigation system	Smart irrigation system powered by solar energy	-SM A/AIO, humidity & temperature sensors, and outputs to operate irrigation pumps
(Liao et al., 2021)	Horizontal (greenhouse)	Controller, wireless sensor, control nodes, irrigation server, remote monitor app, mobile app	Remote automatic irrigation system based on SM	Drip	Tomato	Monit. water needs of crops at different growth stages	NI	Northern China	SIS based on real-time SM	Installed wireless SM sensor to obtain real-time SM information from a 0-100 cm soil profile	Crop evapotranspiration, weather data, crop transpiration, SW, SM data, volume of irrigation, temperature, humidity
(Podder et al., 2021)	Horizontal (field)	Remotely monitoring and controlling an ESP8266 module with the "Thing-Speak" server	NI	NI	NI	NI	Low	Bangladesh	IoT-based smart agrotech system	Based on the condition of the land, remote system decides to start/stop the irrigation.	Humidity and temperature measuring sensor (DHT-11), SM sensor, controller ESP8266

References	Green roof	Smart/IoT/ Technology	Irrigation Scheduling	Irrigation System	Plant Types	Plant growth monitoring	Cost	Climatic conditions	Name of SIS	Generic Description	Instruments/ Data
(Goap et al., 2018)	Horizontal (field)	Sensor node, cloud web-based (real-time data)	SM utilized in the smart scheduling algorithm to effectively use the data on the natural rainfall	NI	NI	NI	High	NI	IoT-based SIS using machine learning	IoT-based SIS using machine learning & open-source tech.	VH-400 SM sensor, Soil temperature sensor, DHT-22 temperature and humidity, UV light radiation sensor
(Roopaei et al., 2017)	Horizontal (field)	Cloud, Wi-Fi, web-based, smart app, GSM, LTE	Monitoring algorithm for identifying the need for water using image processing techniques	Drip	Wheat, corn, tropical fruits	Real-time data of climate, crops, soil	Low	NI	Thermal imaging	Thermal imaging-based intelligent irrigation system	Irrigation temperature distribution measurement (ITDM) by thermal imaging
(S. Kumar & Kusuma, 2016)	Horizontal (experiment)	ZigBee, web-based, remote monitoring app, mobile app (smartphone)	Algorithm developed using temp. and SM threshold, and was set up in a microcontroller-based gateway to control water flow	Drip	NI	NI	Cost-effective	India	WSN and GPRS Module	WSN and GPRS-Based Automated Irrigation System	Temperature sensor, SM sensor, ARM7 microcontroller, GSM, LPC2148 16X2 LCD
(Tiglao et al., 2020)	Horizontal (field)	Web-based, remote irrigation monitoring app, mobile app (smartphone)	Reliable multi-hop WSN system with ad hoc routing algorithm for prolonged lifetime and fault tolerance	Drip	NI	NI	Low	NI	Agrinex	Wireless mesh-based SIS by collecting real-time data	ATMega328 microcontroller using Arduino development board, SM sensor (DFRobot), temp. & humidity sensor (DHT-11), RF24, wireless module
(Jaguey et al., 2015)	Horizontal (field)	Web-based, mobile app, WiFi, cloud-based, Bluetooth	Automated irrigation sensor	NI	Pumpkin crop	NI	NI	NI	Smart phone Irrigation Sensor	Sensor uses a smartphone to capture digital images of soil of crop & estimates water contents	Microcontroller, smartphone, irrigation sensor, ambient temperature, soil condition (moisture), classification, and color

Legend

	Relevant data for developing SIS		*Un-relevant/ missing data*		*Data on case-study or irrigation system*

Note. NI, no information; ID, irrigation dates; IoT, Internet of Things; SM, soil moisture; PD, plant development; SW, soil water content; SIS, smart irrigation system; WSN, wireless sensor network; GPS, Global Positioning System; VRI, variable rate irrigation; URI, uniform rate irrigation; LCD, liquid crystal display; LTE, long-term evolution; GSM/GPRS, general packet radio service; SMS, Short Message Service; ISS, Irrigation scheduling services; SCADA, supervisory control and data acquisition; UV, ultraviolet; XBee, radio communication transceiver and receiver; and ZigBee, Zonal Intercommunication Global-standard.

A recent study by Mirás-Avalos et al. (2019) explores the irrigation advisor, a smart system based on weather forecasts. Another work by Podder et al. (2021) that consider three crucial variables is the IoT-based Smart AgroTech system: soil moisture, temperature, and humidity. Depending on the condition of the plant, the system decides whether to start or stop the watering operation. It also offers remote control and monitoring system. Goap et al. (2018) designed a smart irrigation system using machine learning and open-source tools to support forecast information and present it for future requirements.

Furthermore, other case studies include Shaker and Imran (2013), who developed WSN technology based on climate to monitor the irrigation water management system. Moreover, Katyara et al. (2017) developed a WSN with the SCADA system to improve irrigation efficiency. It was decided to adopt a solar management system to power sensor nodes at irrigation fields. With the use of soil moisture sensors and the drip irrigation automation WSN application, Dursun and Ozden (2011) developed a smart irrigation system. It is an affordable wireless managed irrigation system that monitors the soil-water content in real-time.

The study conducted by Robles et al. (2015) uses a digital platform for data analysis and observation to achieve optimal irrigation management. The WSN was used to monitor and control the quality of water in different weather and climate situations, such as rain, flood, drought, etc. However, the research conducted by Robles et al. (2015) does not offer a solution for the multiple node coordination issues with an optimal irrigation system. Through the critical analysis of these studies, a strong causal role for effective planting can be sustained by observing water quality and plants' maintenance through SIS.

As evidenced by the literature, conservation of water has been achieved through the use of irrigation systems. Thermal imaging and direct soil water measurements are other various framework techniques that further aid in supplying and managing water. Thermal imaging, with a thermal camera, is the most effective means for an irrigation system (Testi, 2018). Based on thermal imaging data gathered using a drone-installed camera, Roopaei et al. (2017) designed an SIS. The algorithm for irrigation scheduling was developed using image processing methods to identify irregular irrigation, water requirement, and leaf water potential.

Zhao et al. (2018) provided another proposal for wireless sensor network application via soil moisture sensors that seek to better manage the irrigation technique's variable rate. A comparison of uniform and variable rate irrigation was undertaken according to the assessed stability of the amount of water in the soil. In this experiment, the recommended variable rate irrigation procedure indicated that there had been significant water saving, changing the pattern of soil moisture. This study also presents the quantities of fertilizers used to increase plant productivity, including phosphorus (P2O5), nitrogen (N), and potassium (K2O).

Most of the information presented in the literature supports the idea that several older irrigation control systems did not take into account climatic conditions, including precipitation, when making irrigation choices. Thus, excessive rainwater used to irrigate plants results in energy and water waste and reduction of plant growth. Such instances can be resolved via IoT-based solutions that use online weather-projecting data to provide enhanced irrigation decision support. Moreover, as technology develops, such as satellite images, weather conditions' precision and accuracy are improving. The development of the SIS in accordance with smart technology connections, dynamic soil moisture patterns of the plants, and future climatic conditions is crucial for effective and effective irrigation of water use.

The relevant literature review papers in Table 12 have been examined to understand and choose the most suitable SIS for SGRs. As a result, it is with clear evidence that there occurs a lack of IoT studies with respect to smart irrigation system papers for green roofs. As an alternative, it can be observed that more articles have been published recently presenting smart- and IoT-based irrigation systems for improvements in farming and agriculture (García et al., 2020). Therefore, there is a gap in knowledge in this matter.

Environmental influences affecting weather- and soil-based irrigation systems that have been closely monitored are discussed (Table 13). The performance of the irrigation system is affected by various conditions and parameters. The efficiency of an irrigation system is influenced by the plant, soil, water, and weather conditions. According to their significance, these four parameters have been studied and proposed in various studies. As indicated in Table 13, the studied literature reviews illustrate the irrigation system's monitored environments and the frequency with which each parameter has been mentioned. This presents the least and most important irrigation influences. The most important parameter is soil moisture, as shown in the systematic literature review 85 times. In addition, most of the published papers concluded that irrigation depends on soil moisture measurements (Dursun & Ozden, 2011; Katyara et al., 2017; Mirás-Avalos et al., 2019; Todorovic et al., 2016; Zhao et al., 2018). According to evidence-based research, advancements in irrigation practices are multifactorial and are the result of monitoring and measurements of soil temperature and moisture, relative humidity, air temperature, and other variables (García et al., 2020; Goap et al., 2018; Kim et al., 2008; Olberz et al., 2018; Podder et al., 2021; Shaker & Imran, 2013).

Table 13. Publications of monitored environments that propose an irrigation system

Smart Irrigation Technology	Monitored Parameter	Number of Peer-Reviewed Publications
Weather-Based	Solar radiation	8
	Carbon dioxide	9
	Air temperature	65
	Relative humidity	60
	Wind speed	5
	Rain	4
	Sound	2
Soil-Based	Soil moisture	85
	Soil temperature	16
	Water level	20
	Potential hydrogen (pH)	15
	Water flow	8
	Water conductivity	2
	Water temperature	3
	Plant height	2
	Soil nutrients	1

The advantages of SIS are maximized by gathering and monitoring data on humidity, temperature, and soil moisture using sensors. Table 14 highlights the trending sensors found in recent literature and indicates the frequency of use. The three parameters' most frequent trending sensors have been classified.: soil sensor VH400, mentioned nine times; temperature sensor DHT11, mentioned 28 times; and humidity sensor DHT11, mentioned 35 times. This numerical information assists in selecting the most appropriate sensor for the different parameters of this research. The trending sensors for humidity, temperature, and soil moisture are all essential in choosing the most suitable SGR system for this research.

Table 14. Recent literature review studies of trending sensors (Adapted from: Goap et al., 2018; Guruprasadh et al., 2017; Krishnan et al., 2020; Mirás-Avalos et al., 2019; Podder et al., 2021; Shaker & Imran, 2013; Tiglao et al., 2020; Zhao et al., 2018)

Temperature		**Humidity**		**Soil moisture**		**Carbon Dioxide**	
Name of instru-ment	**Number of publications using the instrument that have been peer-reviewed**	**Name of instrument**	**Number of publications using the instrument that have been peer-reviewed**	**Name of instrument**	**Number of publications using the instrument that have been peer-reviewed**	**Name of instru-ment**	**Number of publications using the instrument that have been peer-reviewed**
DHT-11	28	**DHT-11**	35	**VH-400**	9	**Testo 160IAQ**	20
LM35	15	**DHT-22**	15	**EC-5**	8		
DHT-22	12			**TDR-3A**	8		
TMP-36	1			**YL-69**	9		

1.3.3.3 Innovative Smart System Outcomes based on Morphological Thinking

The morphological analysis creates a structured procedure that examines all relationships to identify the most suitable SGR system. As mentioned in the previous section, the initial phase was defining and identifying the relevant parameters that impact SGRs. Afterward, as highlighted in Table 14, each parameter is specified and chosen further, following the prominent and significant trends. Meanwhile, some sensors fall short regarding this search's need for more digital analytics and what it is anticipated to measure. As a result, several additional instruments have been proposed in conjunction with Avanceon company and Microsoft Azure according to the morphological thinking methodology. These instruments were incorporated due to their compatibility with other integrated platforms utilized in this research. As indicated in Table 15, the optimal solution based on morphological thinking for smart irrigation green roofs includes two-location parameters, four controllers, three smart IoT, five-soil moisture sensors, three-relative humidity sensors, five-temperature sensors, six-irrigation monitoring and scheduling, five-irrigation systems, three-plant types, four-climatic conditions, and three-cost categories. The number of conditions under each parameter indicates the 1,944,000 possible configurations in this matrix segment. This set of guiding principles leads from a large number of potential configurations to a carefully selected and more systematic 128 potential configurations, outlined in Table 15. Narrowing it down into lesser scenarios aids in choosing formulations that are most optimal for an SIS for the green roof system. To do so, one of the main parameters is the climatic conditions in Qatar. This methodological principle and perceptive method reveal new scenarios and developments in the subject matter, leading to new relationship discoveries while testing the limits of cohesive and interchangeable parametric factors (Zwicky, 2013).

Table 15. Optimal solution based on morphological thinking for a smart green roof's irrigation system

Location	Smart/ IoT	Controller	Temperature Sensors	Humidity Sensor	Soil Moisture Sensor	Irrigation System	Irrigation Monitoring and Scheduling	Plant Types	Cost	Climatic condition
Green roof	*Cloud-based high scalability*	*ESP8266*	*DHT11*	*DHT11*	*VH 400*	*Sprinkler system*	*Based on dynamic irrigation depth*	*Light plants*	*Low*	*Hot*
Green wall	*Sensor data wireless network (less costing)*	*Arduino Uno*	*LM35*	*DHT-22*	*EC-5*	*Drip system*	*Based on constant irrigation depth*	*Medium plants*	*Med*	*Hot Arid*
	Algorithm implementation	*Raspberry Pi*	*DHT-22*	*EM300-TH*	*TDR-3A*	*Drip sprinkler system*	*Constant irrigation volumes*	*Heavy plants*	*High*	*Semi-Arid*
		IRRIOT	*TMP-36*		*YL-69*	*Capillary system*	*Based on ET*			*Arid*
			EM300-TH		*BGT-SM1*	*Manual system*	*Empirical irrigation regime*			
							Based on constant moisture			

Different types of irrigation systems were identified according to the evaluation of several existing systems to illustrate the innovative advanced model. The aim was to develop innovative results and recommendations tailored to SGR structures in Qatar's hot arid climate. The most ideal solution for an IoT smart precision irrigation green roof system, according to morphological thinking, is presented in Table 15 and illustrated in Figure 23. The selected scenario for the smart Internet of Things system is cloud-based for remote control, storage, and access. A suitable controller for SGRs is a wireless irrigation IoT automation platform (IRRIOT), an optimal irrigation method that accurately supplies the needed water for each intended zone (Zaina et al., 2020).

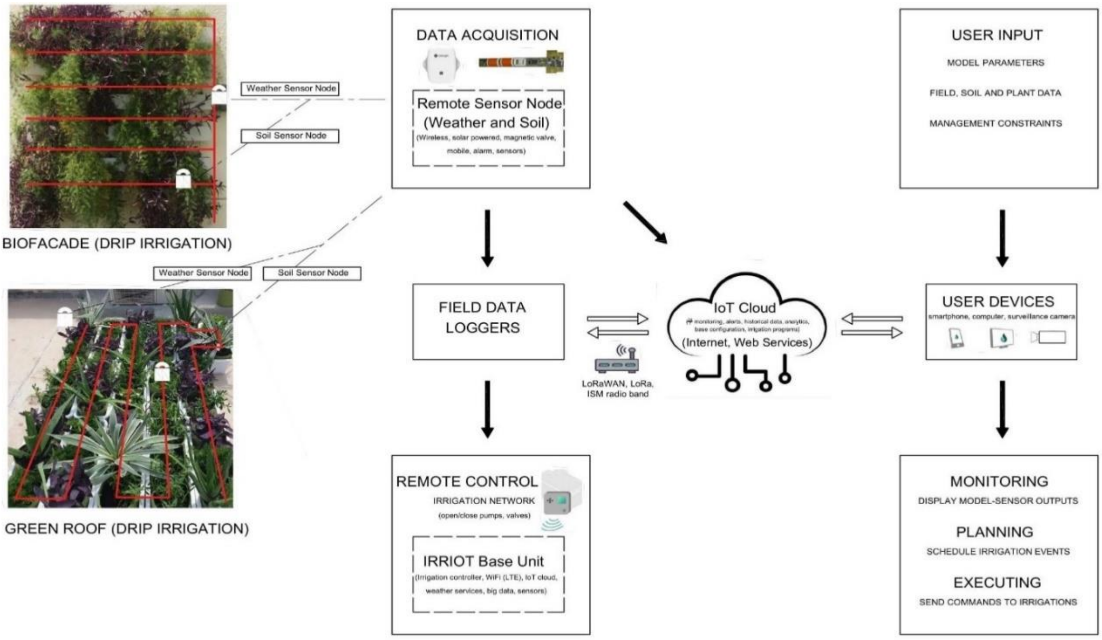


Figure 23. IoT-based smart precision irrigation platform for optimal smart green roofs. *Note*. Top left photo taken from own work in "Biofacades" green wall NPRP 7-1406-2-507 research project in Qatar University; bottom left is real-time smart green roof experiment located in the experimental office building.

IRRIOT uses a two-way wireless cloud-based communication controller (base unit), a central computer that electrically operates the wireless valve control station from any remote location within a 1-5km range. The base unit, linked to Microsoft Azure IoT Hub, has a series of push buttons that allow various watering setups. It is also responsible for the daily failure events, soil state monitoring, preconfigured watering schedule, and other variables. Additionally, the remote device is an outdoor, solar-powered field device that can operate up to two valves and has a variety of mounting choices. The IRRIOT remote cloud-based control, through internet and mobile application, aids in monitoring base and remote unit alarms, manual valve and a series of remote activations, states of sensors and valves, the connection of third-party sensors, weather reports, and configuration of programs (*Wireless Precision Irrigation IoT Platform*, 2019). The IRRIOT system is an environmentally and economically sustainable solution allowing precise and reliable monitoring of soil moisture conditions and variations regularly using water (*Wireless Precision Irrigation IoT Platform*, 2019; Zaina et al., 2020).

As shown in Figure 24, the appropriate sensors compatible with the monitoring of plants, based on the morphological approach outcome, include the Milesight IoT cloud-based EM300-TH wireless temperature and humidity sensor. Enabling sensor mapping allows the device to send mobile push and email notifications in response to triggered events. Moreover, the BGT-SM1 soil moisture sensors are accurate because they are directly compatible with the IRRIOT controller and measure the drip irrigation system's data. The LoRaWAN gateway (UG65-L00E-868M-EA) also links sensors and the cloud, gathering and sending data from sensors to the cloud.

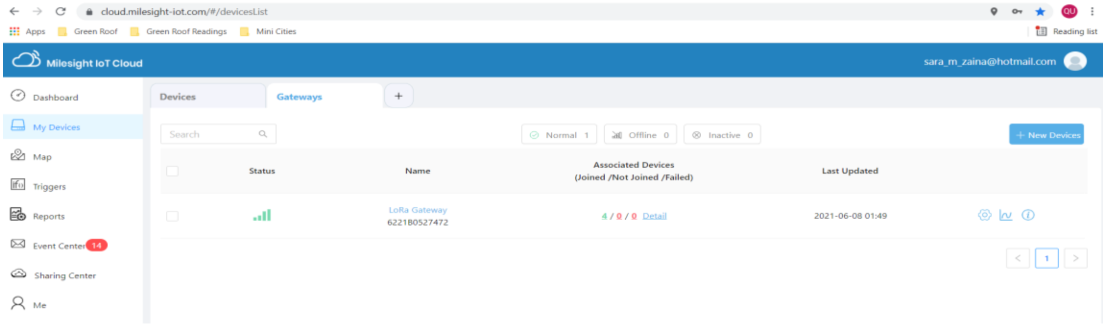


Figure 24. Milesight IoT cloud, including LoRaWAN Gateway and four EM300-TH sensors.

Developing an ability to acquire data without manual interventions in inputs and outputs is the future of SIS. This has been accomplished by concentrating on the soil sensors to track variations in soil moisture levels and the internet for fast access to climatic data by employing various communication methods, including radio, Wi-Fi connections, and smartphone applications. The monitoring of plant growth is therefore managed by sensors, controllers, and a closed-circuit television with a pan-tilt-zoom (CCTV PTZ) surveillance camera, such as video streaming, day and night mode, 360-degree motion, and zoom in-out function. Incorporating all devices creates a platform that allows effective watering, which initially was impractical.

In summation, if water is provided sustainably, SGR approaches can conserve energy by water scheduling, mitigate the UHI effect, and preserve cooling-heating insulation. Thus, implementing efficient irrigation methods increases field productivity and helps save water resources. These smart technologies implemented in green roof systems are the solution for the next commercial SGR systems. The main idea of this system is to minimize human effort and overwatering, thereby ensuring appropriate maintenance of plants.

1.4 Advantages and Disadvantages of Green Roofs

The advantages and disadvantages of a green roof can be categorized into three main groups: environmental, social, and economic. The sections to follow revolve around advantages and disadvantages of green roofs, according to existing literature.

1.4.1 Advantages of Green Roofs

A green roof contributes to a sustainable society (Berndtsson et al., 2009). Sustainable architecture and green roofs aim to reduce the negative environmental impact of buildings. The UHI effect mitigation is established with green roof installation or use. The plant coverage aspect of green roofs, depending on plant type, allows for the absorption of solar radiation. Correspondingly, water vapor release from plants reduces heat infiltration into the building. Equivalently, plants improve the outdoor space for building inhabitants by reducing noise, improving air quality and hydrology, and encouraging biodiversity. This is achieved through the elements of the SGR attributed to plant height, leaf area index, and soil properties.

Several journal articles do not support the green roof advantages with empirical evidence. Study designs differed concerning coherency in construction type definition and methodology. Thus, comparative analysis between construction system types and their associated benefits became difficult to find a causal relationship (Scharf et al., 2012; Yogananda et al., 2015). There has been an indirect correlation between the green roof construction type and its benefits.

However, there remains the need for further studies that compare the various types of green roofs and their varying contributions to improving air quality and the need for those that consider which construction types of green roofs work best in which environment and climatic region. Empirical studies have been published concerning the reduction of noise pollution, yet there is still room for further research. This section aims to introduce environmental, social, and economic advantages to SGR implementation in Qatar.

1.4.1.1 Environmental Advantages

Environmental advantages are myriad due to the implementation of a green roof. These are improvements towards mitigating the UHI effect, improving thermal performance, reducing air pollution, reducing noise pollution, positive impacts on hydrology (reducing stormwater runoff), and increasing habitat biodiversity (Figure 25).

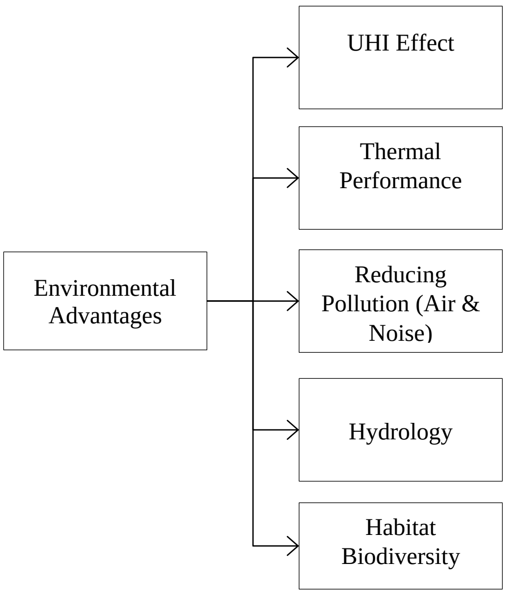


Figure 25. Environmental advantages of green roofs (Adapted from: Santamouris, 2014; Foustalieraki et al., 2017; Athemes, 2017; Renterghem, 2018; Carson et al., 2013; Living Roofs, 2021).

An environmental advantage of green roofs is mitigating UHI effect and enhancing thermal performance. Qatar has undergone massive urban growth and expansion such that several concrete buildings have provoked the loss of green vegetation, causing the UHI effect (Maley et al., 1990). When there is an increase in temperatures, there will be an increased air conditioning load in buildings. As a result, the air conditioning energy load causes more exhaust air to be released into the atmosphere, thus, accelerating the island heat effect. These can be reversed through the growth of live vegetation that reduces surface and air temperatures through the absorption of direct heat (Santamouris, 2014). Accordingly, the implementation of green roofs becomes effective in reducing the negative UHI effect.

Recently, the hot climate of Qatar has been depicted by the outrageous climatic condition of high solar radiation and air temperature, causing significant heat gains through building structures in the urban setting. In such a climate, the use of air-conditioning systems to cool the space in buildings results in significant energy consumption. In addition, the built environment in urban areas increases the atmospheric humidity and air temperatures, therefore, causing the UHI effect. The urban heat island effect has a significant impact on global warming and air pollution at the urban scale.

It is imperative to note that the heating and cooling abilities of green roofs highly rely on climatic conditions and the characteristics of the building. Green roofs are known to have more thermal capacity compared to bare roofs. A conventional roof with dark surfaces retains solar radiation, increasing the temperature of the building (Scherba et al., 2011). However, the incorporation of the green roof absorbs 70-90% of solar energy, cooling the surfaces of the building (Akbari, Pomerantz, & Taha, 2001; Tan et al., 2005; Whittinghill et al., 2014). This phenomenon of green roofs shields the bare roof structure from solar radiation and high temperature, which aids the longevity of rooftops, enhances their long-term performance, and improves their lifespan (Zuriea et al., 2015). Furthermore, green roof materials, such as soil and water, have high thermal mass and can store heat, effectively stabilizing the roof's temperature (Liu & Baskaran, 2003).

Green roofs can thus reduce the energy consumption for air conditioning due to their accompanied shading, evapotranspiration, wind barriers, thermal mass, and insulation capacities, further mitigating the UHI effect and greening the building in the process. The substrate thickness and water improve thermal comfort cooling the building structure (Rosasco & Perini, 2019). Corroborating this finding, Suszanowicz & Kolasa-Więcek (2019) show that green roofs reduce cooling energy needs by 30% for the upper-level floors. Consequently, environmental advantages are reaped due to reduced CO_2 emission due to decreased energy consumption (Suszanowicz & Kolasa-Więcek, 2019). Studies show that with even a 20cm depth layer of growing medium, green roofs have cooling energy savings modeled up to 25% (Ragab & Abdelrady, 2020; Sunakorn, 2010). This paper categorizes climate according to the Koppen-Geiger classification system in connection to the location, as pointed out by Lin et al. (2013), shown in Table 16.

Table 16. Thermal performance of extensive, extensive modular tray system, and intensive green roofs

Type of Green Roof	Climate (Koppen Classification)	Thermal (Heating/ Cooling Performance)	Source
Extensive	Csa Af Bwh Cfb Csb Cfa A Cfa	Cooling performance	(Foustalieraki et al., 2017; Y. He, Yu, & Zhao, 2015; Lin et al., 2013; Manso et al., 2021; Sunakorn, 2010)
Extensive Modular Tray system	Aw Af	Cooling performance	(Sunakorn, 2010)
Intensive	Csa Cfb Cfa Cwa Cwa Not much research has been conducted on intensive green roofs and their thermal performance levels in different climates.	Cooling performance	(Darkwa et al., 2013; Jim & Tsang, 2011; Manso et al., 2021)

Note. Csa, Mediterranean; Af, tropical rainforest; Bwh, tropical (hot) desert; Cfb, marine (marine west coast); Csb, Mediterranean; Cfa, humid subtropical; A, tropical humid climate; Aw, tropical savanna; and Cwa, subtropical monsoon.

The thermal performance varies in the different climate zones. In one instance, a study in Athens, Greece, experiencing a Mediterranean climate, showed that extensive green roof systems with heraclioticum plants reduced heating and increased cooling effects by 11.4% and 18.7%, respectively (Foustalieraki et al., 2017). In another instance, Italy's Mediterranean climate was studied, sedum-covered extensive green roof usage generated 100% thermal energy reduction in the summer, and 30-37% heat loss was attained in the winter (Bevilacqua et al., 2016). A similar empirical field experiment of an extensive green roof system in the Shanghai district's winter climate showed that the thermal performance of the green system in a humid subtropical climate reduced the surface temperature fluctuation by 23.5°C (He et al., 2015). This strongly correlates green roofs with the energy performance of buildings, as per hot climates, such as Qatar (Mahmoodzadeh et al., 2019).

Studies have demonstrated the causal role of green roofs in optimal energy efficiency for all climates. Intensive green roofs reach 84% energy saving in the cooling climate and 48% in the heating climate. However, extensive green roof systems work more efficiently during the heating season, saving up to 52% of energy (Manso et al., 2021). The standard energy consumption for buildings decreases as space conditioning lessens a result of the heat flow moderation of green roofs by more than 75% (Kyle Liu & Baskaran, 2003). In addition to energy-saving potential, greening the building is integral in realizing sustainable buildings.

As presented in Table 17, air pollution reduction results from a green roof acting as a filter of air pollutants and aiding in dust control, leading to improved air quality in and out the building. The plants on the building's green roof stimulate dust absorption on their foliage, concurrently deterring entry into buildings or the public. Considering urbanization and reduced vegetation, the tendency is towards lower oxygen levels and increased carbon dioxide levels, as the lack of plants causes an inability to absorb the excess CO_2 (Santamouris, 2014). The green structure will facilitate the absorption of carbon dioxide in photosynthesis, with a result of oxygen and glucose molecule generation. The roots of the plants also have a role in removing toxic chemicals, lowering the toxin concentrations near green-roofed buildings, and leading to improved air quality as a consequence of purified air.

Table 17. Reduction of air pollution due to green roof usage

Type of green roofs	Type of construction	Results	Source
Extensive/ Intensive	NSP	Extensive green roofs can reduce air pollution in cities, but intensive green roofs are more effective in doing so	(Hop & Hiemstra, 2012)
Intensive	NSP	There are lower concentrations of toxins on top of an intensive green roof system	(Suszanowicz & Kolasa-Więcek, 2019)
Intensive	NSP	-Chicago: a total of 1675kg of air pollutants removed by 19.8 ha in one year through the usage of green roofs -It is estimated that 2046.89 metric tons of pollutants would be removed if intensive green roofs were installed on all of Chicago's rooftops	(Yang, Yu, & Gong, 2008)
Extensive/ Intensive	NSP	Singapore: 37% of $S0_2$ can be captured from the air through vegetation and substrate in green roofs	(Berndtsson et al., 2009)
Extensive/ Intensive	NSP	Los Angeles: suggested that 350 tons of NO_2 /day can be reduced by implementing green roofs	(Rosenfeld et al., 1998)
Extensive	NSP	Detroit: extensive green roofs can remove over 800,000kg/year of NO_2, 0.5% of that area's emissions	(Rosenfeld et al., 1998)
Extensive/ Intensive	NSP	- Yang et. Al (2008) states that green roofs remove 2.33–3.57 g/m^2 NO_2 in an urban environment per year - Jayasooriya et al. (2017) states that green roofs remove 0.37 g/m^2 NO_2 per year	(Athemes, 2017)

Note. NSP, not specified precisely; kg, kilogram; ha, hectare; SO_2, sulfur dioxide; NO_2, nitrogen oxide; and g/m^2, grams per square meter.

Notably, air pollution reduction is heavily influenced by the location condition and types of plants of a green roof system. The appropriate composition and substrate thickness are also crucial factors that need to be studied to achieve maximum filtered air quality. Moreover, large and rough branches, leaves, and twigs are effective tools for removing dust pollution in the air (Suszanowicz & Kolasa-Więcek, 2019).

Veisten et al. (2012) advocate the role of green roofs in reducing noise, concomitantly amplifying natural and artificial sounds with high-quality micro and macro spaces, encompassing a holistic ‘soundscape entirety’ (Veisten et al., 2012). The noise attenuation from green roofs involves outdoor noise absorption and indoor insulation from the outside noise (Cahill et al., 2007; Pittaluga et al., 2011). These noise-allocated disturbances are amplified by conventional rooftops that increase the sound levels of road, rail, air traffic, and industrial noise. Instead, the green roof structure is a non-homogeneous surface that consists of drainage layers, vegetation, granular material, and other high sound absorption characteristics (Pittaluga et al., 2011). A study by Van Renterghem and Botteldooren (2011) reaffirmed that vegetated roofs have significant noise reduction capacities compared to non-greened flat roofs. Van Renterghem's (2018) results strongly advocated a value of 3dBA in traffic noise reduction from a flat green roof relative to a flat rigid roof. The main influencing factors affecting the sound levels of the street are the façade height, street width, diffusion degree, absorption coefficient of the façades, and receiver positioning (Heutschi, 1995). The influencing factors affecting reducing noise levels of green roofs are the thickness, plant type, growing medium, and plant coverage (Tolderlund, 2010).

Green roofs noise reduction mainly works for low-frequency sounds. Sound is reduced by 40 decibels by an extensive green roof and by 46-50 decibels by an intensive green roof (Onder & Akay, 2016). Accordingly, the intensive roof system is strongly evidenced to reduce the sound reverberation of urban noises, with maximum absorption at a 400 hertz (Hz) frequency. Extensive green roofs follow with a maximum reduction of 10dB for frequency absorption of 1000Hz (Pittaluga et al., 2011).

Extensive green roofs are still considered to have excellent noise reduction because it consists of granular materials with open pores, making them an essential element property where sound penetrates and interacts with particles, leading to noise attenuation (Timothy Renterghem, 2018). Modular tray systems are structured to reduce noise over 10dB at both mid and high-frequency ranges. An overview of the reduction of noise resulting from green roof implementation is presented in Table 18.

Table 18. Reduction of noise due to green roof usage

Types of green roofs	Types of Construction	Results	Source
Extensive/ Intensive	NSP	Green roofs have excellent noise attenuation	(Cahill et al., 2007; Pittaluga et al., 2011)
Extensive/ Intensive	NSP	Green roof mitigates diffracting sound waves through acoustically rigid materiality, being a practical solution for sound absorption in dense urban traffic cities	(Renterghem, 2018)
Extensive/ Intensive	NSP	-Conventional rooftops increase the sound levels of road, rail, air traffic, and industrial noise -Green roof structures and materials have high sound absorption characteristics	(Pittaluga et al., 2011)
Extensive/ Intensive	NSP	The noise attenuation from green roofs involves outdoor noise absorption as well as indoor insulation from the outdoor noise	(Cahill et al., 2007; Pittaluga et al., 2011)
Extensive/ Intensive	NSP	The influencing factors affecting the effectiveness of reducing noise levels of green roofs are the thickness, plant type, growing medium, and plant coverage	(Tolderlund, 2010)
Extensive/ Intensive	NSP	Green roofs noise reeducation mainly works for low-frequency sounds	(Onder & Akay, 2016)
Extensive	NSP	An extensive green roof reduces sound from outside by 40 dB	(Onder & Akay, 2016)*
Intensive	NSP	An intensive green roof reduces sound by 46-50 dB	(Onder & Akay, 2016)*
Intensive/ Extensive	NSP	Study by Pittaluga, Schenone, and Borelli reveals that an intensive roof system is strongly marked with the best performance to reduce sound reverberation of urban noises, with maximum absorption at a frequency of 400 Hz. Extensive green roofs come second with a maximum reduction of 10 dB for frequency absorption of 1000 Hz	(Pittaluga et al., 2011)*
Extensive	NSP	Extensive green roofs consist of granular materials with open pores, making it an important element property where sound penetrates and interacts with particles, leading to noise reduction	(Renterghem, 2018)
Extensive	Modular Tray System	-Trays become structures that help reduce noise -Significant effect on noise reduction, with more than 10 dB, at both mid and high-frequency ranges -Position, material, and vegetation all have to be taken into account and calculated as they affect the results of noise reduction -Larger the surface area of the system, the stronger the noise reduction effect	(Yang, Choi, & Kang, 2010)*

Types of green roofs	Types of Construction	Results	Source
Intensive/ Extensive	NSP	-Sound reduction occurs through sound absorption and diffusion happens when sound impinges on the vegetation and is reflected, as well as by sound reduction, which occurs when sound transmits through the vegetation	(Gedge, 2002)
Intensive/ Extensive	NSP	Numerical simulations show that flat green roofs provide 3dBA traffic noise decline relative to a flat rigid roof	(Renterghem, 2018)*
Extensive	BioSOLAR systems	Green roofs with solar panels have been shown to decrease sound pressure levels up to 5 dBA. This indicates that adding solar panels harvests not only higher solar energy efficiency but also increases noise shielding	(Renterghem, 2018)

Note. NSP, not specified precisely; *, denotes empirical study; dB, decibels; Hz, hertz; and dBA, A-weighted decibels.

As an advantage to green roof systems, the effects of hydrology were the most broadly explored, where many comparative papers recorded the water runoff data between different construction systems. They indicated the different profiles of the types and their retained volumes of stormwater runoff and measured peak runoff flows. However, it is imperative to note that the results of different studies can vary significantly due to various factors, including the distribution and intensity of rainfall events, seasonal evapotranspiration rates, and research approaches. Thus, it was necessary to select studies that recorded the runoff effects over a long period. Descriptive studies concerning the reduced volume of stormwater runoff and the positive impacts and advantages hydrology have on green roofs are presented in Table 19. This helps achieve water balance objectives, water quality, and stream channel erosion control (Cahill et al., 2007).

Table 19. Positive effects on hydrology due to green roof usage

Types of green roofs	Type of construction	Results	Source
Extensive	NSP	-Runoff and precipitation were monitored during 154 runoffs where the extensive green roof discharged 63% less runoff than a bare roof -Reducing runoffs, controlling peak flows, and the timing of flows play a positive role in mitigating the effects of stormwater	(Van Seters et al., 2009)*
Extensive	Pre-grown mat system	Promotes runoff movement to varying degrees	(Carson et al., 2013)*
Extensive	NSP	Rooftop garden delayed and reduced runoff results have replaced the impermeable roof surface through the delay of peak flow	(Liu, 2002)*
Mostly Extensive/ Intensive (the study only talks in terms of extensive)	Modular Tray System	Allows restriction of surface runoff through the tray walls and provides corrugated air space for drainage through its base. This prevents surface flow and ponding that cause erosion of the substrate	(Carson et al., 2013)*
Extensive/ Intensive (the study only talks in terms of extensive)	Built-in-place	A specialized drainage course helps surface flow and ponding. Drainage was continuous, and water existed on the substrate vertically in contrast to drainage at the base of each modular tray	(Carson et al., 2013)*
Extensive	BioSOLAR roof system	Least effective in reducing stormwater runoff and peak flow	(Ciriminna et al., 2019)
Intensive	NSP	Intensive systems retained 88.6% compared to the intensive system containing 74%.	(Razzaghmanesh & Beecham, 2014)*

Note. NSP, not specified precisely; and *, denotes empirical study.

Green roofs thus play a significant role in minimizing several runoff volumes and peak flows gathered by the drainage system, reducing investments for the drainage system, playing a crucial role in lowering floods and pollution masses, and impacting overall improvements in the climate. Research conducted by Kolb (2004) established approximately 45% of all rainfall is recycled. In another study, green roofs can reduce runoff by 60-100% depending on the green roof system and construction type (Ibrahim, 2018). Similarly, the technology could minimize the peak flow rate by an estimated 22-93% (Getter & Rowe, 2006).

Liu and Minor (2005) investigated the effect of green roofs on the reduction of runoff volume and flow rate. Two green roof test plots were compared with significant results to the control roof. Stormwater runoff monitoring was through drainage pipes that were connected to flow meters. Data was collected on a one-minute time interval. The authors purport that green roofs effectively reduce stormwater runoff, depending on the amount of rain and soil performance. Evidence from the experimental research shows an average annual reduction of 57% in stormwater flow volume from the green roof in comparison to the control roof. However, the study failed to test stormwater quality during the experiment.

Further, experimental tests and studies on the hydrological performance of green roofs have demonstrated that the technology can delay the peak flow by an estimated duration of up to 30 minutes (Getter & Rowe, 2006). These hydrological performances are crucial in reducing floods, pollution, and erosion during rainfall events. Recently, several studies showed the importance of green roofs in mitigating combined sewer overflows pollution and reducing urban stormwater runoff challenges (Carson et al., 2013; Berndtsson, 2010).

Runoff and precipitation were monitored during 154 runoffs, where the extensive green roof discharged 63% less runoff than a bare roof. The main factors influencing the variations in the rates were rainfall volumes, evapotranspiration rates, and moisture content. The findings indicated vegetated roofs help mitigate the effects of stormwater by reducing runoffs, controlling peak flows, and timing (Van Seters et al., 2009). Another extensive empirical study was conducted on the pre-grown mat system, modular system, and built-in-place system showing the positive effects on hydrology. Results presented that the modular tray had the highest retention rate and was the most efficient at decreasing total runoff volume compared to others. The built-in-place system was the most effective in lowering the number of combined sewer overflows events rather than decreasing volume of stormwater.

Meanwhile, while the pre-grown mat system didn't have the best rainfall attenuation performance, it was the most constructible due to its cost and significant lightness. The modular system had the highest retention percentage, and the pre-grown mat system had the lowest. In the modular system, multiple outlets manage drainage at the base of each tray (Carson et al., 2013). Compared to the different green roof construction systems, BioSOLAR green roofs are the least effective in reducing stormwater runoff and peak flow (Ciriminna et al., 2019). Razzaghmanesh and Beecham (2014) carried out a study comparing the runoff data between extensive and intensive green roofs for almost two years. Extensive systems retained 74%, and the intensive system retained 88.6%, indicating that both profiles retained significant volumes of stormwater runoff and could attenuate peak runoff flows with good delay times regardless of the substantial difference in depth of soils.

However, it is imperative to note that the effectiveness of empirical studies can vary because of design attributes. These variations in the design of green roofs make it difficult and daunting to generate performance predictions (Rakotondramiarana et al., 2015). According to most literature, the hydrology of green roofs is determined by green roof construction type, vegetation type, soil depth, precipitation dynamics, precipitation volume, and roof slope (Niachou et al., 2001). It is essential to note that the variables that directly impact green roof hydrology cannot be used to predict the expected performance due to the lack of an appropriate model (Zuriea et al., 2015).

Existing literature suggests that green roofs help restore wildlife habitats, as presented in Table 20, in constant threat. Green roofs provide space and coverage to protect wildlife and birds from predators (Liptan & Strecker, 2003). The application of green roofs acts to provide food and water, such as insects, berries, and seeds, to feed birds, thus restoring habitats for invertebrates, birds, and other animals (Fernandez-Canero & Gonzalez-Redondo, 2010). Studies have confirmed that fungi, bacteria, and arthropods, such as beetles, spiders, true bugs, ants, bees, wasps, flies, 44 species of springtails, and mites, were presented in installed green roof spaces (John et al., 2014; Joimel et al., 2018; Ksiazek-mikenas et al., 2018; Kyro et al., 2018; Madre et al., 2013; Molineux et al., 2015; Rumble & Gange, 2013).

Table 20. Habitat biodiversity resulting from extensive and intensive green roofs

Type of green roofs	Type of construction	Results	Source
Extensive/ Intensive	NSP	-Green roofs provide space and coverage to protect wildlife and birds from predators -Green roofs provide food and water, such as insects, berries, and seeds, to feed birds	(Fernandez-Canero & Gonzalez-Redondo, 2010)
Extensive/ Intensive	NSP	Several bird species, including hummingbirds, blue jays, swallows, pigeons, sparrows, hawks, or owls, are observed in the nest in the city of Portland	(Liptan & Strecker, 2003)
Extensive/ Intensive	NSP	European climate green roofs provided habitats for 176 plant species on 115 green roofs	(Mayrand & Clergeau, 2018)*
Extensive/ Intensive	NSP	Six Swiss cities identified 91 out of 532 species (17%) located on green roofs	(Pétremand et al., 2017)*
Extensive/ Intensive	NSP	A study suggested that both birds and arthropods were richer and more plentiful on green roofs than on bare roofs	(Partridge & Clark, 2018)*
Extensive	NSP	-Extensive systems with only plants like sedum and without a watering system have been shown to offer the best habitat results for wildlife out of all extensive roof systems. -Other types of extensive systems that do not have these qualities offer a habitat only for plant species	(Hop & Hiemstra, 2012)
Extensive	Pre-grown mat system	Advantages a limited range of invertebrate species, and the sedum flowers provide food for pollinators, such as bees	(LivingRoofs, 2021)
Extensive	Biodiverse habitats system	Specially designed for improving biodiversity with its composition of substrate depth and wide range of wildflowers and sedum planted	(LivingRoofs, 2021)
Intensive	NSP	The habitual component is controlled by the type of system and substrate composition making intensive systems have greater potential to maximize biodiversity	(Hop & Hiemstra, 2012; Hui & Chan, 2011)

Note. NSP, not specified precisely; and *, denotes empirical study.

In addition to restoring wildlife habitats, green roofs encourage biodiversity by supplying habitats with flora and fauna (Rafida et al., 2011). Empirical studies of green roofs and their effect on improving biodiversity in urban areas include areas in the European climate where habitats for 176 plant species were located on 115 green roofs (Mayrand & Clergeau, 2018). Another recent study in six Swiss cities identified 91 out of 532 species on green roofs (Pétremand et al., 2017).

Restoration of wildlife and natural habitat have been better studied, comparing biodiversity between different green roof types regarding species diversity and richness, substrate depth, plant species selection, and connectivity to the landscape. Empirical studies also suggest that green roofs have presented species, particularly birds and arthropods, with more suitable nesting, food, and shelter spaces. Exploring the function of green roofs as habitats, the study by Brenneisen (2006) has demonstrated that extensive green roofs are suitable for increasing both plant and animal biodiversities in cities under extreme climate conditions.

Comparably, research in Switzerland and the United Kingdom shows that extensive green roofs provide a wide collection of wildlife and biodiversity, especially insects and birds (LivingRoofs, 2021). In strong correlation to these findings, an assessment comparing biodiversity between extensive and intensive green roof systems was established by Hui and Chan (2011). This includes:

- Species diversity and richness: green roofs intensive type slightly overshadow green roofs extensive type
- Substrate type and depth: green roofs intensive type considerably overshadow green roofs extensive type
- Plant species selection: native species slightly overshadow exotic species

- Connectivity to natural vegetation: the more the connection to the urban landscape, the better
- Green roof ratio: the higher the green roof area ratio to the building, the better (Hui & Chan, 2011)

With such varying factors that affect the habitat biodiversity of green roofs, the assessment of the effectiveness of green roofs goes beyond mere types of construction. However, concerning species diversity and substrate composition, intensive green roofs are shown to be more effective in maximizing the potential of biodiversity.

1.4.1.2 Social Advantages

According to Tolderlund (2010), the social advantages of green roofs include adding aesthetic quality to the urban environment, softening the building's environment, supporting biodiversity, increasing urban agriculture, enhancing public spaces, reducing electromagnetic radiation by up to 94%, reducing waste volumes, and lowering noise levels to 40-60 decibels (Onder & Akay, 2016).

The evidence presented in a recent study conducted with a sample size of 155 respondents supports the hypothesis that the visual characteristics of green roofs affect the respondents' preferences. Three main green roof constructions were investigated: cuttings system, pre-grown mat system, and modular tray system (Vanstockem et al., 2018). Green roofs have become transformative features reconstructing an unappealing blank concrete roof into a visually aesthetic green space (Rahman & Ahmad, 2012). Furthermore, green roof studies have found that visual perception of a natural rather than a built environment reduces patient recovery time and leads to improved health and horticultural therapy, thus positively influencing mental health and well-being (Abass et al., 2020; Tolderlund, 2010).

The literature for empirical studies on the visual effects of green roofs is steadily increasing. The inquiry and exploration of users' interactions to the visual perception of green roof types have been considered. Inclusion of the different types of plantations, whether shrubs, native forbs, grasses, topical, and other vegetation, are also being studied, as well as the structural variation and diversities of green roofs. Importantly, comparisons of users' desirability between vegetation type, conspicuous weed, and roof area gap have been tackled. Using semi-closed questionnaires, Sant'Anna et al. (2018) were able to study differences between users'; the results of this study showed significant user satisfaction from green roofed buildings over conventional ones in Brazil.

Natural views decrease anger and increase calm. This improves business profitability since it has been hypothesized that enhancing people's physical or emotional comfort can expand productivity. It improves the aesthetic appearance of the city as a green tourist destination which will, in turn, positively impact the economy. Furthermore, green roofs foster a sense of community, creating an interactive space for people to visit, enjoy, and relax (Velazquez, 2005). Table 21 presents an overview of the social advantages of green roof adaptation.

Table 21. Social advantages to green roofs

Type of green roof	Type of construction	Results	Source
Extensive and Intensive	NSP	-Improved aesthetics with a unique and desired quality of visual significance -Increases property values -Enhance public spaces	(Tolderlund, 2010)
Extensive and Intensive	NSP	-Encourage city planning by increasing amenities and green space -Creating places for recreation and rest	(Susca et al., 2011)
Extensive and Intensive	NSP	Green roofs link us to the world around us, and their visual beauty needs to be experienced, engaged, and learned from	(Sutton, 2014)

Type of green roof	Type of construction	Results	Source
Extensive and Intensive	NSP	One-way green roofs can be engaged with is by simply having building users overlook lower neighboring buildings' green roofs, thus improving views & user mood and wellbeing	(Archtoolbox, 2021)
Extensive and Intensive	NSP	Visual studies show that structural variation and diversity in species and plants positively affect the user. While messiness in green roof vegetation has a negative impact	(Jungels et al., 2013; Lee et al., 2014)*
Extensive	Cuttings system	-Vegetation type: Dominated by sedum weed -Very conspicuous weed -75% of the roof area gap -Least desirable	(Vanstockem et al., 2018)*
Extensive	Pre-grown mat system	-Vegetation type: Combination of sedum and herbaceous plants -Barely conspicuous weed -5% of the roof area gap -Most desirable	(Vanstockem et al., 2018)*
Extensive	Modular tray system	-Vegetation type: Dominated by herbaceous plants -Conspicuous weed -75% of the roof area gap -Less desirable	(Vanstockem et al., 2018)*
Extensive	Loose-laid system	-Most varied and integrated vegetation among extensive systems	(Tolderlund, 2010)
Extensive and Intensive	NSP	-Proven to reduce electromagnetic radiation by up to 94% -Noise level reduction of up to 40-60 decibels -Improved health and horticultural therapy, reducing patient recovery time -Reduction of waste volumes -Increase in urban agriculture (food production in the city)	(Tolderlund, 2010)
Extensive and Intensive	NSP	-Improves psychology of human health and wellbeing -Reduced stress and lowered obesity when in proximity -Positive impact on people where employee productivity increased with green living environmental green in comparison to those without	(Gidlöf-Gunnarsson & Öhrström, 2007)
Extensive and Intensive	NSP	-Linked to a reduction in crime	(Donnelly, 1992; Tolderlund, 2010)
Extensive	Biodiverse habitats system	-Offer environments for rare and imperiled species	(Dunnett & Kingsbury, 2008)
Intensive	NSP	-More aesthetic appeal and suitability for public access with higher presence than extensive	(Cahill et al., 2007)

Note. NSP, not specified precisely; and *, denotes empirical study.

Comparably, a lack of consensus exists regarding influencing factors from differing construction types that affect social advantages. Social advantages of green roof types have been studied, such as improved productivity and health, while relying heavily on various social contexts. This is because social engagement and community satisfaction depend not only on the aesthetics and types of green roofs but also on the context, region, culture, and type of setting in which the green roof is allocated. Thus, this needs to be considered to understand better the impact of green roof construction type and its design while noting what the aesthetics of the feature can bring to public and social spaces. A two-year study conducted by Liu and Minor (2005) in Toronto, Canada, was designed to examine the advantages of green roofs, in particular, quantify the social benefits to the environment and climate that arose due to the implementation of a green roof. Comparably, Yogananda et al. (2015) meticulously designed seating arrangements to habituate conversational groupings on green rooftops. Evidence from these studies indicates that green roofs fostered social connection and socialization.

1.4.1.3 Economic Advantages

This section discusses the economic advantages of green roofs, including saving energy costs. To achieve around 15% of annual energy saving, cities must develop green structures, including green roofs. This can reduce cooling loads by up to 80%, causing a downsizing of the air conditioning systems resulting in savings in capital investments for construction. Further, rooftops can be used as viable alternatives to thermal insulation. A Tokyo, Japan study showed that if 50% of the roofs were covered with green roofs, the air temperatures could reduce from a total of 0.11°C to around 0.84°C. When these figures are translated to dollar currency, it would be approximately $1.6 million saved daily in electricity bills (Villarreal & Bengtsson, 2005). Green structures are of significant cost-effectiveness and should thus be adopted by Qatar to enjoy these advantages.

1.4.2 Disadvantages of Green Roofs

Green roofs have several disadvantages that can hinder their application and progress. The application of green architectural elements in Doha can face a myriad of disadvantages that may jeopardize progress and hinder the advantages associated with green structures.

1.4.2.1 Environmental Disadvantages

Doha is the capital city of Qatar and is situated along the country's coastal region (Santamouris et al., 2007). It is imperative to note that the climatic conditions in this desert region cannot support a myriad of vegetation. The hot temperatures and high humidity are not suitable for most plant species. Green roofs will be vulnerable to high temperatures (38°C) and elevated humidity levels throughout the year. The extreme sunlight and heat will make the plants wither before demonstrating their advantages. Green roofs are highly vulnerable to strong winds, and the region experiences strong sand-filled winds that may damage the vegetation on green architectural elements.

1.4.2.2 Social Disadvantages

In addition to the environmental and economical building structure features, green roofs are associated with aesthetic value. However, the aesthetic value is mostly dependent on the subject design of green roofs. Some green roofs, while performing the intended task of energy-saving, are less appealing to the eye. Green roofs are vulnerable to social issues that may arise on aesthetic grounds. Critics of green roofs may argue that they tarnish the city's beautiful skyline. Also, adopting green roofs all over the city may challenge its urban status.

1.4.2.3 Economic Disadvantages

The cost and labor associated with the installation and maintenance of green roofs present an economic weakness to green structures (Shafique et al., 2018). Green roofs require additional structural support, giving rise to a new building structure design that can withstand the weight associated with green roof installation.

The type of green roof adopted determines the additional weight to the structure. When implementing GR, around 50 to 200 kg per square meter is added to the original weight of the structure; thus, there is a need for further consideration of structural support. If not adequately catered for, the roof of the building may collapse, destroying the green roof and the whole building. Constructing a new green roof is similarly very expensive; thus, thorough consideration must be accounted for.

While green roofs can be more beneficial in many aspects than the bare system, they are more expensive than conventional roofs. The cost of constructing or incorporating additional roofing support is of higher monetary value than the conventional system. Research evidence shows that the amount of money required to construct and incorporate additional structural support is very expensive, depending on the green roof to be adopted in the building (Scholz-Barth, 2010). Further, additional costs will be incurred in maintaining the live vegetation, so that they grow and perform their intended purpose.

The expense for developing extensive green roofs relies on the incorporated components, including the soil, nature of roof membrane, drainage system quantity, and plants. The Environmental Protection Agency (2009) report anticipated that the preliminary cost for an extensive green roof is USD 10/m^2 (Shafique et al., 2018). The maintenance expenses of extensive green roofs are reduced when the plants entirely cover the roof area (Zaina & Fadli, 2020). Whereas for an intensive GR, also portrayed in the Environmental Protection Agency (2009) report, it was presumed that the preliminary cost for an intensive roof are up to USD 270/m^2 (Shafique et al., 2018). The maintenance costs of intensive green roofs, similar to extensive green roofs, remain constant when the roof is entirely covered by plants (Zaina & Fadli, 2020).

1.5 Conclusion

Green roof history, taxonomy, and advantages and disadvantages must be understood to allow for an effective application of this research study. This chapter aimed to identify the taxonomy of green roofs, including typologies, design considerations, and smart systems. The design considerations to be closely monitored are geographic location, climate, structural systems, and plants and growing medium selection. This is to understand better how such design considerations can be used, influenced, or manipulated to serve the purpose of implementing an SGR system. When SGR systems are criticized for being a causal component to user thermal comfort in a building, several mechanisms must be considered: environmental, social, and economical. Smart irrigation systems and their impacts are also studied. The research paper further explores existing smart irrigation technology, whether weather-based or on-site soil moisture-based, and their monitoring requirements. These factors ultimately lead to comprehending the advantages and disadvantages of a green roof installation on buildings in hot arid climates, including environmental, social, and economical.

Moreover, relevant literature reviews have been examined to identify and choose the most suitable SIS for SGRs. Accordingly, there is clear evidence of a lack of research concerning SIS papers for green roofs. In contrast, most studies on smart irrigation systems concern irrigation for plant gardens, agriculture, and farms.

Therefore, there is a knowledge gap in this area.

Additionally, the chapter delivered a review of the technical aspects of SGRs, of which a series of recommendations is being provided below for an optimized, sustainable modular roof system in the hot arid region of Doha, Qatar, based on existing systems while protecting or minimizing investment and offering convenience, with the integration of a smart-based irrigation system. Above all, the enhanced modular system completes the sustainability offered in hot arid regions environmentally, socially, and economically.

- Roof type: light structure (extensive roof system)
- Structure: vegetation layer, soil layer or growing medium, drainage layer and membrane layer, waterproofing and filter layer, root barrier, and wireless irrigation IoT automation platform (IRRIOT).
- Installation technique: modular.
- Plant types: plants must be selected according to the building's location and orientation where wind, sun, shading, and rainfall build-ups. Some suitable plants for Qatar include Aptenia (Haialam), Sesuvium portulacastrum, Asparagus Ferns, Tradescantia Pallida, Aloe Vera, Agave Americana, Euphorbia MillBig, Pennisetum Setaceum, Eremophila Maculata, and Ruellia brittoniana.
- Soil type: the growth medium should be cautiously designed to offer good plant growth and appropriate water-holding capacity. Once the plant is selected, the right soil type must be chosen to support them. The soil should contain low organic content to enhance fire-resistant properties. The thickness and composition of the soil are important features in plant selection.

- Plant parameters: plant height depends on the roof type; LAI is typically in the range of 0.5–5.0.
- Smart irrigation system: to achieve the most optimal smart irrigation system, it was necessary to consider a variety of variables, including IoT/smart/technology, plant types and growth monitoring, irrigation system and scheduling, climatic condition, cost, and instruments. The use of efficient plant growth sensors that measure temperatures, soil moisture, and relative humidity, such as trending sensors including the EC5, TDR3A, DHT22, and DHT11, is one of the most important recommendations for IoT remote-based irrigation control. An SIS, or precision irrigation system, is particularly practical for hot arid regions as it enables real-life monitoring and easy control of environmental factors such as evaporation, soil, weather, and water usage by plants, allowing for effective tailoring and adjusting of the watering schedule in accordance. Wireless controllers are highly recommended in hot, dry areas to decrease labor-intensive SGRs. Remote control devices, such as IRRIOT, offer access to precise and reliable sensor data monitoring, watering schedules, watering time adjustments, and magnetic valve activation. SIS controllers, sensors, and irrigation systems are environmentally and economically viable for effective water usage in hot arid regions.

In conclusion, this chapter provided a contextual and theoretical background on green roofs. The following chapter deals with appropriate literature review exploration. In this sense, presently occupying green roofs on a building are explored to examine the state of its successful components.

CHAPTER 2: CASE STUDIES OF GREEN BUILDINGS FOCUSED ON GREEN ROOFS

2.1 Introduction

Green buildings have become essential as an innovative solution for architecture around the globe to reduce footprint and provide environmental protection. Understanding and evaluating the case studies examined in this chapter is essential to design, develop, and implement smart green roofs (SGRs) in hot arid climates.

A closer look into green roofs was inherent by establishing a selection criteria through means of geographical location based on climatic condition. Taking an international perspective at first, followed by a regional viewpoint, final zoning into the case study location was recognized. This thorough examination allowed the investigation of existing green roofs to inhibit the use-case with the major benefitting parameters.

2.2 Case Studies Selection Criteria

Although rooftop gardens are quickly adopted in western urban settings, not much about their performance is known when applied in hot arid climatic conditions, in which water restrictions and drought severity diminish a plant’s survival chances. In such regions characterized by water shortage, essential conflicts between resource-conscious water management and rooftop gardens' irrigation must be evaluated. The selection criteria for the case studies are primarily determined by the locations being in hot and arid climatic zones. The case studies divulge from a global to a local perspective, exploring international, Middle East and North America (MENA) region, and local Qatar green roof implementations, summarized by a matrix of the eight case studies analyzed. This macro-to-micro approach is to establish a cultural perspective of green roof use, first in an international setting, then with a more focused impact on their use in more closely related settings, and finally with a look at existing green roofs in the country under study. The selected case studies analyze the following parameters. This is to establish a suitable SGR design for a hot arid environment: type of building, location, date of development, green roof area, roof type and slope, plant types, depth and type of growing medium/soil, description, irrigation system, smart applications to the roof system, and advantages and disadvantages of implemented green roof.

2.3 International: WorldWide

The international section consists of describing green roof design and its associated advantages. It includes three case studies: Western Australia in Australia, Yangon in Myanmar, and Texas in the United States.

2.3.1 Case Study of Western Australia, Australia

Project name	Florence Street (O'Donoghue, 2016)
Building image	 Figure 26. Florence Street, Australia.
Type of building	House
Architect	Emilio Fuscaldo
Date of development	2015
Type of roof	Extensive
Slope of roof	3 degrees
Green roof size	50 m²

Depth of soil	20 cm
Plants	- The plants were selected due to the soil being very permeable - Sir Walter Buffalo replaced Kidney Weed (Dichondra repens) after it died off in the summer - Growing successfully is Lamb's Ears (Stachys bizantina), Blue Chalk sticks (Senecio Serpens), Hen & Chicken plant (Echivera glauca), Inland Pigface (Carpobrotus modestus), and Blue Flax-lily (Dianella revolute)
Description	- Sustainable - Green roof is an extension of the landscape, creating harmony with the environment - Water collected from the roof feeds into the toilet, and is used on both the roof garden and dwelling's ground garden
Green roof advantages	- Reduced urban heat island effect - Acts as an insulation layer - Enhance the aesthetics of buildings - Encourages diversity in flora and fauna

2.3.2 Case Study of Yangon, Myanmar

Project name	Parkroyal Hotel (Smallwood, 2022)
Building image	 Figure 27. Parkroyal Hotel, Myanmar.
Type of building	Residential
Type of roof	Semi-intensive green roof
Slope of roof	2 degrees
Green roof size	100 m^2
Depth of soil	25 cm

Plants	Tropical plants
Description	- Sustainable buildings that are integrated into their environment - Hotel incorporates greenery and other sustainable features such as rainwater harvesting and solar water heating
Green roof advantages	- Reduce UHI effect and heat transfer through buildings - Helps insulate the building - Enhance air quality - Improve building aesthetics and increase habitats - Expands roof life by protecting the waterproofing layer from temperature changes - Enhance users' comfort in the building

2.3.3 Case Study of Texas, United States

Project name	Austin central library (Rosenberg, 2018)
Building image	 Figure 28. Austin Cerntal Library, United States.
Type of building	Library
Architect	Lake|Flato Architects and Shepley Bulfinch Joint Venture
Date of development	2017
Type of roof	Intensive green roof
Slope of roof	2 degrees
Green roof size	500 m^2
Depth of soil	15-30 cm
Plants	Live oak tree, as well as other trees and plants indigenous to the area

Soil	- 20-30% compost - 10-20% sand - 60% expanded shale
Description	- The building includes greenery and other sustainable features such as an energy-efficient HVAC system and a rainwater harvesting system that collects rainwater for irrigation and toilet flushing. - Landscaping on the rooftop
Green roof advantages	- Reduce high temperature and UHI effect - Improve air quality - Beautify buildings and cityscape - Supports local biodiversity

2.4 Regional: Middle East and North Africa Region

This section presents three case studies in the Middle East and North Africa (MENA) region, including the American University in Cairo, Dubai Opera Garden green roof, and Al-Shaheed Park in Kuwait.

2.4.1 Case Study of Egypt, New Cairo

Project name	Desert Development Center / American University in Cairo (AUC's) (AUC100, 2013; Gawad, 2014)
Building image	 Figure 29. Desert Development Center, New Cairo.
Type of building	University
Architect	American University in Cairo
Date of development	2013

Type of roof	Extensive Green Roof
Slope of roof	3 degrees
Green roof size	300 m²
Structure and components	Sheltered with succulent plants that are located on a waterproofing membrane
Description	- Research aims at helping the Desert Development Center promote green roofs in Egypt to enhance the users' comfort level - Creates a space for learning (different types of plants, irrigation systems and drainage) - Composed of heavy conventional soil and sand - Planters on rooftops are filled with various types of soil media, including perlite, mixes of peanut shells, compost, vermiculite, sand, and crushed clay pots
Green roof advantages	- Serves a variety of environmental and economic purposes - Provides bees, insects, and birds with a natural habitat - Aesthetically appealing, produce vegetables and enhances food security - Enhances air quality - Reduce UHI effect, solar radiation, and carbon dioxide - Provides natural cooling for the indoor rooms below the building
Green roof disadvantages	- Requires maintenance

2.4.2 Case Study of Dubai, United Arab Emirates

Project name	Dubai Opera Garden Green Roof and Vegetated Terraces (Greenroofs, 2020)
Building image	 Figure 30. Dubai Opera Garden, United Arab Emirates.

Type of building	Commercial/public
Architect	Janus Rostock, Atkins
Date of development	2017
Type of roof	Semi-intensive green roof – accessible
System	Single-source provider
Slope of roof	2 degrees
Green roof size	3,000 m²
Insulation	Knauf insulation green solutions
Depth of soil	Less than 15cm
Plants	- Sesuvium and native paspalum grass were planted - The mineral growing media that was used allowed for the plant’s survival in the hot, harsh climate, as it retains water so that plants can absorb it Shrubs were planted, including Ruellia, zoysia grass, Agave, Adenium, and Bougainvillea - Shrubs were planted in a combination of mineral and sweet soil growing media
Irrigation	Drip irrigation
Description	- Aesthetically appealing and comfortable space compared to surroundings - Plants used adapted to hot and dry climate conditions - Green roof was composed of a low irrigation system - Hydro blanket was used as a mineral growing media - 10cm of growing media profile was used (lightweight system) - Types of semi-intensive green roofs installed: small, elevated roof system for plant testing and an open green park space
Green roof advantages	- Improves air quality, cools city temperatures, reduces UHI - Insulates from heat and noise - Creates new open space for recreation and food growing - Supports physical and mental health and aesthetically pleasing

2.4.3 Case Study of Kuwait

Project name	Al-Shaheed Park (Hani, 2013; IGRA, 2018; ZinCO, 2020)
Building image	 Figure 31. Al-Shaheed Park, Kuwait.
Type of building	Public
Architect	The Associated Engineering Partnership (TAEP), Kuwait Projects Company (KIPCO), Sharq, Kuwait
Date of development	2018
Type of roof	Intensive Green Roof
System	ZinCo system build-up “Landscaped Underground Garage” with Stabilodrain® SD 30
Slope of roof	1 degree
Green roof size	80,000 m²
Plants	- Native plants were used exclusively - Selection of both plants and shrubs adapted in a hot arid region - Palm trees include Phoenix Dactylifera - Trees that were used include Callistemon Viminalis, Tabebuia Argentea, Acacia Arabica, Parkinsonia Aculeata, Prosopis Chilensis, and Citrus-Lime - Shrubs that were used consist of Agave Attenuate, Carissa Woodbox, Euphorbia Tirucalli, Atriplex Helimus, Duranta Repens, Tabernaemontana Diviricata, Nerium Oleander, Leucophylum Frutescens, Jatropha Pandurifolia, Zamia Furfuraceae, Rosemarinus Officinalis, and Adenium Obesum
Irrigation	Automated irrigation system

Description	An appropriate example of a green roof system was adopted, which met the challenges of hot, dry climatic conditions
Green roof advantages	- Reduces desertification, air pollution, and global warming - Reduce urban heat island effect, solar radiation, and carbon dioxide - Reduce air temperature and humidity level

2.5 Local: Qatar

Three case studies are presented, having been selected wholly as they belong to this dissertation's local hot arid region, Qatar. Namely, the New College of Engineering at Qatar University and public areas such as Pearl and Katara cultural village.

2.5.1 Case Study of New College of Engineering at Qatar University, Qatar

Project name	New College of Engineering Building
Building image	 Figure 32. New College of Engineering building at Qatar University.
Type of building	University
Architect	Mimar Consult
Date of development	In progress
Type of roof	Intensive Green Roof System (accessible)
Slope of roof	2 degrees
Green roof size	225 m²
Type of system	Daku green system

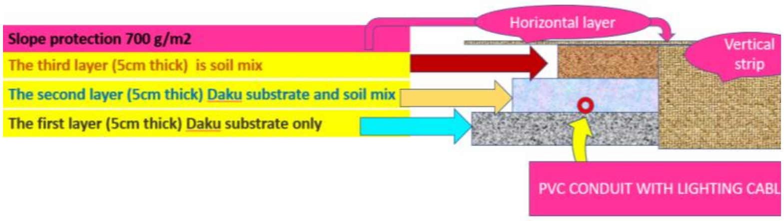


Figure 33. Daku substrate (planting) (Source: Cascone, 2019).

Depth of soil	15 cm
Plants	Sesuvium Portulacastrum (ground cover)
Soil	Sweet soil (composed of clay and dune sand, supplied by MME, compost, and peat moss
Irrigation	Drip irrigation
Description	- New building will be constructed for the New College of Engineering at Qatar University following GSAS green building system. - Rating system: education, GSAS D&B - Certification level: GSAS D&B 4 stars
Green roof advantages	- Reduce UHI effect - Improve exterior air quality and energy efficiency - Aesthetic improvement - Allows for social interaction and gatherings

2.5.2 Case Study of Pearl, Qatar

Project name: Viva Bahriya, Pearl (Al Thulathia green roof, Atlantis)

Building image:

Figure 34. Viva Bahriya, Pearl, Qatar.

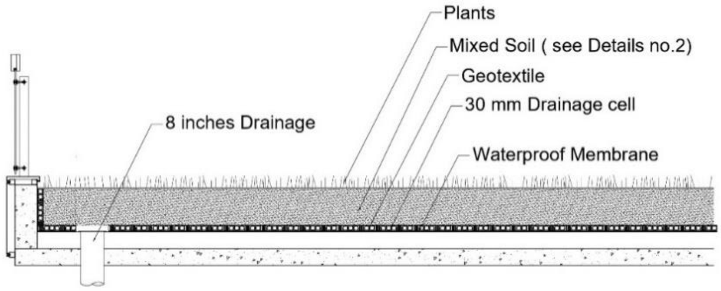


Figure 35. Section of Al Thulathia green roof at Pearl.

Type of building	Public
Date of development	2015
Type of roof	Intensive Green Roof System (accessible)
Slope of roof	3 degrees
Green roof size	500 m²
Depth of soil	20 cm
Plants	Local native plants, including Tradescantia Pallida and Sesuvium
Soil	Soilless poding mix, coco-beats
Irrigation	Automated irrigation system
Description	Pearl is a public space that implements green roofs to achieve the concept of green buildings
Green roof advantages	- Reduces UHI Effect • Promotes natural cooling • Reduced ambient temperature • Shading Surfaces - Improves exterior air quality • Captures atmospheric deposition and pollutants • Filter particulate matter and harmful gases - Aesthetic improvement • Creates appealing visuals and hides unattractive features • Increases the value of property

- Provides fascinating elements

- Improves energy efficiency

- Traps a layer of air within the plants
- Limits heat gain and reduces the ambient temperature
- Creates buffer against wind
- Interior applications decrease the energy required for heating or cooling

2.5.3 Case Study of Katara, Qatar

Project name	Katara
Building image	 Figure 36. Katara cultural village in Qatar.
Type of building	Public
Date of development	2012-2015
Type of roof	Intensive Green Roof System (accessible)
Slope of roof	1 degree
Depth of soil	15 cm
Plants	Varies, however, it is inclusive of local plants such as Tradescantia Pallida, Asparagus Ferns, Aptenia, Sesuvium, etc.
Soil	Sweet soil (composed of clay and dune sand, supplied by the Ministry of Municipality and Environment), mixed soil, compost (Manure, AGRI-QATAR), and peat moss (Nord Agri)

Irrigation	The scope of work and discussion includes the Motorola Irrigation Central Control system for controlling and monitoring all elements and actions in the irrigation system using supervisory control and data acquisition (SCADA). The Control system has four components (Central control system in the control room, Field Interface Units (FIU) in the control room, a Communication system, and Remote Terminal Unit (RTUs). The RTU shall automatically start and stop the irrigation lines based on the following: 1. According to water flow 2. According to the required irrigation schedule.
Description	Katara is a public space that tries to implement the concept of green buildings including green roofs and walls, to enhance sustainable aspects.
Green roof advantages	- Reduce UHI effect - Improve outdoor air quality - Enhance energy efficiency - Allows for social interaction and gatherings

2.6 Conclusion

According to the case studies, Table 22 summarizes the key green roof features from what is learned from the eight case studies. A thorough analysis of case studies from an international, followed by a regional, and then a detail-oriented perspective on the local region, Qatar, a base point to green roof design is elicited. Careful examination of these case studies has been conducted, with an integrative viewpoint into roof type and slope, green roof size, plants used, soil type and depth, irrigation system employed, and whether it has a smart application. Further scrutiny into the advantages and disadvantages of the green roof allows to understand better how to implement particular design aspects into this research study outline.

Table 22. Summary of the key green roof features of eight case studies

Case Study	Type of Building	Location	Year	Green Roof Area (sqm)	Green Roof Type	Roof Slope (degree)	Plants	Growing Medium Depth (cm)	Growing Medium Type	Irrigation	Smart
2.3.1	Residential	International	2015	50	Extensive	3	Lamb's Ears (Stachys bizantina), Blue Chalk sticks (Senecio Serpens), Hen & Chicken plant (Echivera glauca), Inland Pigface (Carpobrotus modestus), and Blue Flax-lily (Dianella revolute)	20	Permeable	N/A	No
2.3.2	Residential	International	N/A	100	Semi-intensive	2	Tropical plants	25	N/A	N/A	No
2.3.3	Library	International	2017	500	Intensive	2	Live oak tree, as well as other trees and plants indigenous to the area	15-30	Compost, sand, and expanded shale	Drip	No
2.4.1	Institution	MENA region	2013	300	Extensive	3	Vegetation and succulent plants	N/A	Perlite, mixes of peanut shells, compost, vermiculite, sand, and crushed clay pots	Drip	No
2.4.2	Commercial/ public	MENA region	2017	3000	Semi-intensive (accessible)	2	- Sesuvium and native paspalum grass - Shrubs: ruellia, zoysia grass, Agave, Adenium, and Bougainvillea	Less than 15	Sweet soil and mineral wool growing media	Drip	No
2.4.3	Public	MENA region	2018	80,000	Intensive	1	Native	N/A	N/A	Automated	No
2.5.1	Institution	Qatar (local)	In progress	225	Extensive (accessible)	2	Sesuvium Portulacastrum (ground cover)	15	-Mineral mixture of lightweight, granulated porous lava and pumice -Sweet soil (composed of clay and dune sand, supplied by MME), compost, and peat moss	Drip	No
2.5.2	Public	Qatar (local)	2015	500	Intensive (accessible)	3	Local native plants, including Tradescantia Pallida and Sesuvium	20	Soilless poding mix, coco peats	Automated	No
2.5.3	Public	Qatar (local)	2012-2015	N/A	Intensive (accessible)	1	Tradescantia Pallida, Asparagus Ferns, Aptenia, Sesuvium	15	Sweet soil, mixed soil, compost, and peat moss	Automated	No

Note. MENA, Middle East and North Africa; sqm, square meter; cm, centimeter; N/A, not applicable; MME, Ministry of Municipality and Environment.

Due to the nature of building structures in the region under study, that of flat roof slopes, the international and MENA region case studies have been selected to observe the features implemented in a similar construction element. Although this selection was intentional, it was inevitable as the roof slopes in hot arid climates are mainly flat and do not exceed 3 degrees. Most residential and commercial cases use an intensive or extensive green roof depending on the location, condition of the surroundings, building area, and environmental factors.

The common mix of growing medium amongst all case studies is sweet soil, compost, peat moss, and coco peat. The literature further explores that these implemented green roofs employ growing mediums at approximately 20cm depth. This is used in the experiment to amplify the performance of the green roof. Most cases use native local plants that adapt to their region as is appropriate to the climatic conditions.

The irrigation system used in case studies is analyzed as a drip or automated. The use of the drip system implies that the water supplied to plants is controlled and evenly distributed among plants in the green roof system. The experimental real-time study adopts this and improves upon it through a smart application. The smart irrigation system in the research is an automated IoT drip irrigation. Thus, there is a need for careful consideration and revision to design, develop, and implement SGRs in Qatar.

Moreover, it is crucial to note that there is an absence of digital technologies to incorporate a smart aspect into the design of green roof systems. Based on the analysis and review of the case studies on green roofs, there is an apparent gap in the association between building energy consumption and user thermal comfort experienced in the building. This research thesis thus aims to discover a balanced solution between these two crucial factors through SGR implementation. The following chapter will delve into the research aspects, divided into both a look into real-time and simulation.

CHAPTER 3: THEORETICAL FRAMEWORK

3.1 Introduction

Over the last couple of decades, there has been an overwhelming interest in the green roof movement toward sustainability practice in architectural and building performance. Empirical research studies based on the implementation of green roofs have been established. A rise in real-time research has been noted, with fewer studies evaluating the use of simulation tools (Figure 37). By critically analyzing a variety of recent peer-reviewed literature publications, this outline aims to identify if plants and green roofs have a causative impact on building thermal performance, energy consumption, and users' comfort. By examining real-time and simulation based research, an experimental and simulated research tool is designed to fulfill the aims and objectives of this thesis to design, develop, and implement SGRs. Given the research conducted in countries with latitudes higher than 40° that experience cold or mild climates, there is a notable lack of evidence-based experimentation and practices that address green roofs in hot arid regions.

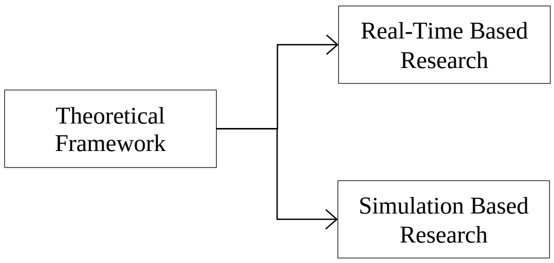


Figure 37. Theoretical framework structure.

3.2 Real-Time-Based Research

There is a lack of literature reviews and empirical studies on extensive and intensive green roof system construction types and their effect on thermal performance levels. The studies did not identify or categorize the construction methods used to study thermal performance. Additionally, the advantage of thermal performance was explored in different climatic regions with other tools, making comparisons between construction systems challenging (Aboelata, 2021; Bevilacqua, 2021; Scharf et al., 2012).

Comparatively, this research insufficiency has also been noted concerning reducing air pollution and noise. There is insufficient literature detailing the type of construction system that improves air quality and reduces both extensive and intensive noise. There is an abundance of articles that classify the type of plants as helpful in reducing air pollution, although not empirically evidenced.

The ability of plants to withstand certain hot climates is discussed, along with the subsequent performance of the green roof. Plant characteristics advocate functional green roof performance, delving into studies that explore plant color, height, and leaf area index (LAI). These features cohesively form an assessment criterion of the plants to assess thermal cooling on the building. This section further looks into microclimatic elements and their association with users' thermal comfort. The explored microclimatic elements include air temperature, relative humidity, and wind speed.

3.2.1 Design of Smart Green Roof

The extensive green roof system involves a thin layer of growing medium which assists in the nourishment of low-growing, stress-tolerant plants that grow independently and require minimal irrigation (Liu & Minor, 2005). Thus, this type of design function offers advantages at minimal costs and limited maintenance. On the other hand, an intensive green roof design is heavy, characterizing high vegetation weighing 200 kg/m^2 and a 150-1500 mm height build-up of green roof. It is appropriate for areas where lawns and bushes, shrubs, and small trees must be planted. These intensive green roofs are also to be associated with complex landscapes and water elements. Mainly utilized in recreational areas such as parks and roof gardens, an intensive roof system must be frequently irrigated and maintained (Zaina & Fadli, 2020).

The modular green roof system offers an innovative roofing design solution proposal and an advanced technological solution with multiple advantages. According to the research, the innovation is a lightweight structural element prefabricated before on-site setup. The modular system comprises various configurations, sizes of heights, and diameters for the green roof structure. The system can also be integrated with smart automatic devices to ensure sustainability. Sustainability is incomplete without focusing its maintenance in terms of smart applications. It is crucial to consider multiple factors when designing and installing a green roof. These include the requirements of international standards, national regulations, green roof codes supported in green buildings, specific climatic regions of the construction area, and other variables, including economic factors and local conditions (Attia, 2020).

Moreover, analyzed findings have revealed an extensive modular tray system as an effective strategy in combatting heat and enhancing the cooling performance on the temperature of the building and the surrounding environment in hot arid Doha. Interestingly, green roof use has been exploited to reduce building energy demand to maintain indoor comfort conditions (Parizotto & Lamberts, 2011; Paulo César Tabares-Velasco, 2009). A 20cm growing medium depth has also reached 52% energy savings in heated climates (Manso et al., 2021). Extensive systems have also reduced large amounts of air pollution and toxins annually. A modular tray system significantly reduces the noise of more than 10dB, as the trays become structures that reduce the noise of high and low-frequency ranges (Pittaluga et al., 2011). As previously mentioned, the trays also restrict surface runoff, provide corrugated air space for drainage through its base, and prevent surface flows that would substrate erosion. Improved aesthetic and user well-being, visual access, increased amenity, better urban agriculture, improved biodiversity, and increased greenery would be added advantages. Its suitability for the climate allows for the full benefit of green roofs on an individual, social, and urban level.

3.2.2 Plant Performance and Assessment Criteria

Meetam et al. (2020) studied the drought tolerance ability of ten plants in Thailand, a country predominantly experiencing hot and humid climate conditions. By placing the potted plants under a shaded area to shield them from the automated sprinkler irrigation system, data was collected at intervals throughout the seven days after the drought treatment. By assessing the environmental conditions during the experiment and comparing plant performance between control and drought, the green roof was found to provide environmental advantages including, but not limited to, mitigation of air pollution, lower carbon dioxide levels, reduction of UHI effect, and absorption of sound (Meetam et al., 2020). Recently, Meetam et al. (2020) investigated the physiological parameters of plants and discovered that plants possess a stomatal opening that can draw in carbon dioxide for photosynthesis, thus, diminishing carbon dioxide in the atmosphere. Green roofs are essential climatic adapters for cities. Having great temperatures and long droughts can negatively impact plantations; in turn, the diversity of plants that could be used becomes limited and more expensive to maintain.

Comparing different plant species, Lundholm, Weddle, and Macivor (2014) found that wetland plants have lower thermal resistance than highland plants. Berardi et al. (2014) analyzed different plant types, including Halimione, Aptenia, Sesuvium, and Pennisetum. They found that Sesuvium and Pennisetum are the most significant to implement in a green roof system (Berardi et al., 2014). As displayed in Table 23, Fadli et al. (2018) conducted an experimental study showing that the most effective types of plants in hot arid regions include Asparagus Ferns, Sessivium Portulacastrum, Pennisetum Rubrum, Rheo Spathacea, Tradescantia Pallida, and Aloe Vera. Getter and Rowe (2006) proposed plants for green roof systems that do not require irrigation, including Sempervivum and Delospermaas.

Table 23. Plant types that adapt in hot arid regions (Source: Fadli, Bahrami, & Zaina, 2018)


Asparagus Aethiopicus (Asparagus Ferns)


Sesuvium Portulacastrum (Sesuvium)


Pennisetum Setaceum Rubrum (Fountain Grass)


Tradescantia Spathacea (Rhoeo Spathacea)


Tradescantia Pallida (Setcreasea Purpurea)


Aloe Vera (Aloe Barbadensis Miller)

Moreover, regarding the possible plant types, Cox (2010) verifies that various plant types can lead to changed values of thermal insulation. Different plant selections in green roof systems lead to substantial differences in the value of thermal insulation. Figure 38 shows that sedum, one of the most common plants, has a short root structure, provides high shading against solar radiation, and requires limited watering (Berardi et al., 2014). Berardi et al. (2014) advocate that sedum provides better shading than other plant types. Moreover, they correlate Ryegrass with air circulation, requiring limited shading (Berardi et al., 2014).

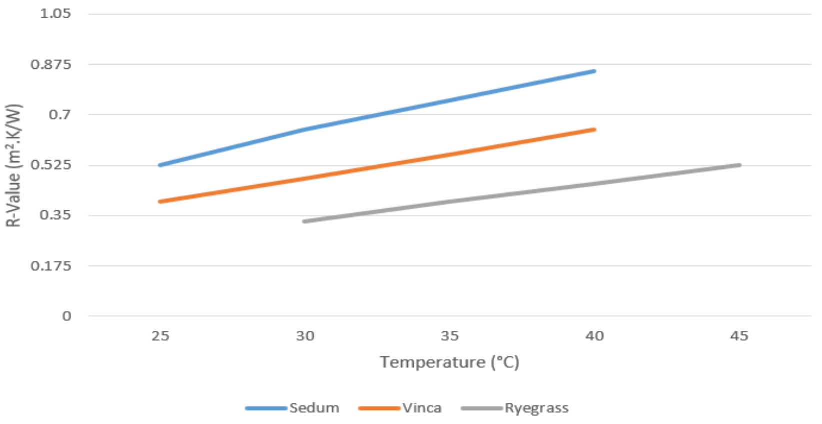


Figure 38. Thermal resistance of different plants (Adapted from: Berardi et al., 2014).

Vegetation can significantly affect the thermal performance of buildings in different climate zones, directly affecting the temperature. Plants may decrease the temperature of an area owing to their absorptive qualities needed for growth and biological functions. Research shows that a temperature decrease ranging from 1-4.3°C is observed on green roofs due to plant shading (Wong, Chen, Ong, & Sia, 2003). Thus, plants act as a solar barrier preventing solar penetration and absorption into a building, providing thermal advantages to the building (Wong, Chen, Ong, & Sia, 2003).

Multiple studies have identified that color, height, and LAI aid in measuring plant performance in green roofs (Barrio, 1998; Friedman, 2017; Kendal et al., 2013; Lundholm, Tran, & Gebert, 2015; Theodosiou, 2009; Wong & Chin, 2018; Yao et al., 2010; Yazdani & Baneshi, 2021). The following paragraphs discuss researched color theories regarding plant performance analysis, studies recording various optimal plant height properties, and LAI simulations and valued rations for optimal plant performance. In addition, information on plant color, height, and LAI provides the means to assess optimal thermal cooling on the building (Figure 39).

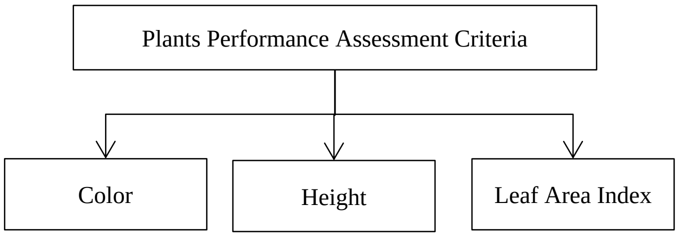


Figure 39. Plants performance assessment criteria of the green roof plants (Adapted from: Barrio, 1998; Friedman, 2017; Kendal et al., 2013; Lundholm, Tran, & Gebert, 2015; Theodosiou, 2009; Wong & Chin, 2018; Yao et al., 2010; Yazdani & Baneshi, 2021).

In an experiment by Kendal et al. (2013), the leaf color of different plant species was compared through quantitative rather than subjective means by analyzing digital images taken from multiple cameras, including digital single-lens reflex and mirrorless cameras. In similar research, color difference, color distributions, and color contrast through digital images between plant species were the main quantitative focus of estimating plant dynamics (Fiorani et al., 2012). This quantitative measure was by differentiating the sizes between two colors. Color distributions entailed using L*, a*, and b* where L* represented brightness, a* represented greenness, and b* represented yellow (Kendal et al., 2013). In a supportive viewport, Yao et al. (2010) analytical study considered color space adopted by the International Commission on Illumination in 1976 (L*a*b*) as an appropriate measure of plant performance and nutrient level.

Furthermore, plant color can provide information on plants' performance concerning providing optimum cooling to the building. Dark-colored leaves absorb the most sunlight energy, and light-colored leaves reflect excess sunlight, resulting in roofs with dark-colored plants providing cooler rooftops in comparison (Wong & Chin, 2018). Overall, varied use of differentiative and quantitative color criteria can be noticed in existing literature concerning the authors' research objectives and aims.

Another important measure to study is plant height. Yazdani and Baneshi (2021) identify optimal plant height as an important factor for the thermal evaluation of green roofs. They propose that green roofs' optimal plant height properties depend on a specific region's climate. With regards to the journal article, Iran's hot climate plant height optimal properties are 0.2m for uninsulated roofs and 0.1m for all other roof materials; and 0.1m independent of roof material. Overall, plant heights varied 0.1m, 0.2m, and 0.3m; it was concluded that the plant height in extreme hot climates should be taller than in cold climates. Another research by Lundholm et al. (2015) considers plant height as a useful trait that helps predict plant growth rate and thus optimize green roof performance. The average plant height determined by manually measuring 21 test species recorded consistently low height in forbs and shrubs, relatively low but highly quantitative for succulents, and high and variably quantitative for grasses, graminoids, and tall forbs. For many literature studies and sensitivity analyses, plant height is considered a general indicator for growth rates and performance and a primary variable in determining thermal transfer into the building (Lundholm, Tran, & Gebert, 2015; Westoby, 1998; Yazdani & Baneshi, 2021).

The level of LAI, as studied by Wong and Chin (2018), mapped that plants with a ratio of 0.15 (15% surface coverage of plants) are considered loose foliage, while a ratio of 1.00 (100% surface coverage of plants) is regarded as dense foliage (Figure 40). The authors also observed the effect healthy plants with high LAI have on the cooling performance of the building. Moreover, the observation stated that more plants and a higher LAI usually signified more growth and offered more shade to the building, reducing solar radiation received by the building and increasing the cooling performance (Wong & Chin, 2018). Similarly, Theodosiou (2009) and Barrio (1998) found that LAI is one of the most relevant parameters for cooling potential. Friedman (2017) instead regarded plant thickness, texture, foliage density, and color lightness as the main parameters influencing the cooling performance of the building. Yazdani and Baneshi (2021) regard LAI as an important factor for the thermal evaluation of green roofs, where LAI values through simulations varied between 0.1, 1, 3, and 5. He concluded that similarly to plant height, optimal LAI and climate have a direct correlation, where optimal LAI tends to decrease for colder climates. Another measured LAI experiment portrayed that leaf area tends to be low for shrubs, and sometimes higher for tall plants such as forbs and succulents (Lundholm, Tran, & Gebert, 2015). Most literature regarding plant performance and its effect on cooling the building identified plant color, height, and LAI as important parameters to explore (Friedman, 2017; Lundholm, Tran, & Gebert, 2015; Theodosiou, 2009; Wong & Chin, 2018; Yazdani & Baneshi, 2021).

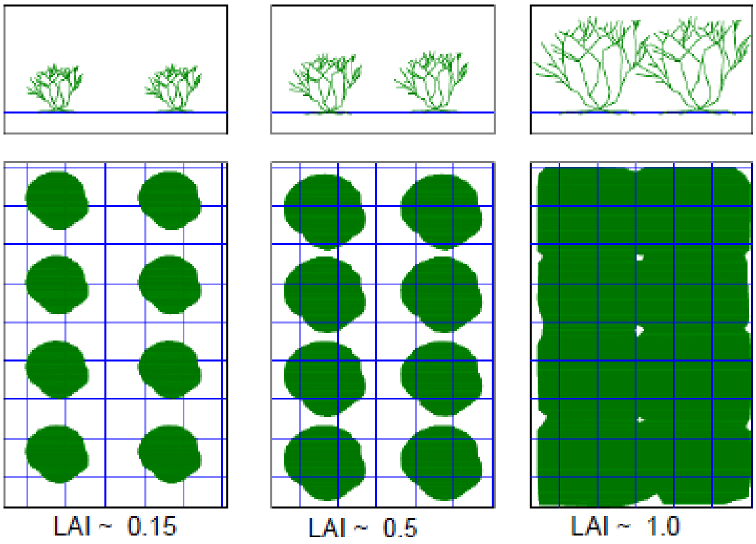


Figure 40. Leaf area index mapping of plant growth (Source: Wong & Chin, 2018).

3.2.3 Microclimatic Elements and Users' Thermal Comfort

The user's thermal comfort is associated with the urban climate and microclimatic conditions. The climate types include cold-cold humid/cold dry, moderately dry/moderately humid, and hot-hot humid/hot dry (Dahl, 2010). Microclimatic elements include air temperature, relative humidity, and wind speed (Bojinski et al., 2014). Due to the variations in climate and various microclimatic parameters, design planning for an outdoor space needs to be considered (Dahl, 2010).

Air temperature directly impacts outdoor thermal comfort. For instance, if the air temperature outside is 21°C, it can be extremely cool in a windy shaded area or extremely warm in a sunny non-windy area. The same temperature could also be perceived differently in other locations. While air temperature affects outdoor thermal comfort, it has little effect on changing air temperature for indoor thermal comfort (Yang, Lau, & Qian, 2011). Specific design strategies may increase or decrease air temperature and thermal comfort indoors and outdoors. Solar exposure using dark materials is maximized to improve air temperature, and cold wind flowing through windbreaks is reduced. To decrease air temperature, vegetation for shade reduces building heat and pavement absorption, and water features facilitate evaporative cooling outdoors (Kontoleon & Eumorfopoulou, 2010). Thus, materials and design strategies can be used to modify the effect air temperature has in adjusting the thermal comfort of users in the space.

Relative humidity is the water vapor that emerges due to the evaporation process of water from surfaces (Konya, 1980). It is expressed as the ratio of water vapor to the equilibrium water vapor pressure of a specific temperature. Thus, it is dependent on both water vapor and temperature. In hot and arid climates, low humidity levels cause excessive heat and discomfort (Konya, 1980). The extreme dryness of the air, as a result of low humidity, can cause a break in lips and soreness in throats (Clark & Edholm, 1985).

In comparison, a high humidity level causes indirect discomfort due to the dispersing of sweat caused to help evaporative cooling. The increased humidity of the skin can be uncomfortable in formal clothing and other circumstances. Studies show that work-related fatigue is usually higher at a high relative humidity of 70% than at a lower 30-40%. For steady and moderate climates, average relative humidity has minimal effect on thermal sensation and comfort. Nonetheless, changes in relative humidity levels from indoor to outdoor, or vice versa, significantly impact thermal comfort (Nikolopoulou, 2011).

The wind speed has an indirect way of affecting thermal comfort in both outdoor and indoor areas. Surrounding context can change wind direction or decrease/increase wind speed, such as trees and vegetation and the neighboring heights and building forms. Trees can reduce wind speed, and high buildings can divert intense wind speed to the ground level. Wind speed can also affect plant performance in green-roofed buildings, thereby increasing or decreasing the efficiency of the plant's effect on the building's indoor thermal comfort (Dahl, 2010).

3.3 Simulation-Based Research

The research on green roofs is constantly evolving. The number of research studies reviewed provides a good overview of the historical significance and way of use for green roofs and the technical aspect. It also illustrates the lack of literature and case studies on the performance and effectiveness of green roofs in hot and arid climates using a simulation software, such as DesignBuilder. Roof system, type, installation technique, plant type and diameter, soil type, and drainage design were some of the few unexplored and not laid out details for installations of green roofs in Qatar and similar countries since little to no research studies were conducted. However, observations in Qatar have told a different story about green roofs. There are a couple of green roof installations in the Pearl and Katara. However, they are unrecorded and unexamined for research purposes. There is a significant gap between researchers in Qatar and those actualizing and implementing green roofs. This causes little to no knowledge exchange and the loss of research advantages and empirical evidence. This section is the starting point of connecting research toward implementing SGRs to contribute to the existing literature. The possible future direction is to evaluate even more specified green roof construction types slowly. Incorporating smart technology research and implementation for green roof systems in hot arid regions will further this. This study aims to prove to be useful for researchers, urban planners, architects, and engineers.

3.3.1 DesignBuilder Simulation – Building Envelope and Users' Comfort

Testing the mitigation effects of green roofs, an extensive green roof long-term simulation was modelled in the case study location of Qatar in the study by Andric et al. (2020). Using DesignBuilder as a simulation tool, green roofs were rendered and modelled. When assessing the green roof parameters, the study proved that the leaf area index (horizontal plant growth) had a significantly higher impact than plant height (vertical plant growth). The building energy consumption was preserved due to plant foliage density and shading effect (reflecting solar radiation). However, this simulation based research questioned the performance of green roofs and their mitigation potential for energy consumption in extreme hot climates. But rather, they favored a polystyrene building envelope coupled with energy-efficient glazing over a green roof. The authors failed to study other positive effects of green infrastructure, failing to simulate green roofs' effects on air quality, UHI effect, and physical and mental well-being and health of users of a building.

Majority of the evidential research agrees on the significant influences green roofs propose on heat transfer. As a corroborating view, Daemei et al. (2019) assert that thermal performance is improved with green roof use in effectively reducing heat transfer. Various climatic conditions in Iran were simulated using DesignBuilder, and energy performance data was acquired by modelling residential buildings in four climates over a single year. It is critical to point out that green roof cover effects are two-fold. First and foremost, they protect the building from environmental impacts. Secondly, they provide environmental advantages. The paper by Daemei et al. (2019) fails to address and justify the user thermal comfort advantages to green roof implementation.

3.3.2 DesignBuilder Simulation – Building's Energy Consumption

Dabaieh et al. (2015) investigate green roof composition solutions through simulation to reduce heat gain. They purport that green roofs are of more energy-efficient capacities than bare conventional roofs (Dabaieh et al., 2015). Green roofs absorb sunlight and heat effectively, preventing heat from entering the building. The advantage of green roof use lies in the confirmed ability to induce aesthetically pleasing comfort and, at times, inflate the economy by attracting tourists (Dabaieh et al., 2015). In strong comparison to these findings, the results of Wahba et al. (2018) demonstrate the effectiveness of green roofs on energy consumption and indoor comfort in the hot arid climate of Cairo, Egypt. Simulating a 15cm extensive soil thickness with the use of the DesignBuilder software, predicted mean vote was reduced by 3, indicating users enhanced indoor thermal comfort, along with a reduction to the entry of solar radiation. This effectively resulted in a significant 43% electricity need reduction. Both papers employed DesignBuilder simulation software to model a hot, dry arid climate. The difference in results and major findings between Dabaieh et al. (2015) and Wahba et al. (2018) most likely owes to the varied simulation components. The former simulated the entire building modelling the heat transfer from neighboring buildings, while the latter simulated the temperature profile with and without greenery, focusing on the case study building.

A horizontal green roof system is a great method to reduce the amount of energy consumed for air conditioning and enhance thermal comfort, both indoor and outdoor, by decreasing heat transfer to and from the building (Stec et al., 2005). According to Pérez et al. (2012), four key issues contribute to the functioning of greenery systems in terms of passive energy savings in buildings and have to be considered for the successful operation of the green roof. First is the construction method employed to place plants on the building structure. Second, the selection of plant species and how the temperature affects its growth are both influenced by the climate, in addition to the thermal behavior of the building. Third, the type of plant species employed, such as whether they are ground covers, shrubs, climbing plants, deciduous or evergreen, etc. Finally, it is important to consider the factors that affect how these green systems function as a means for passive energy savings (Pérez et al., 2012). Kontoleon and Eumorfopoulou (2010), on the other hand, summarize that four main mechanisms define green systems as a passive system for energy savings: the production of shadow by the plants, insulation provided by the plants, and their substrate, barrier effect to the wind, and the evaporative cooling by evapotranspiration.

Plant parameters that affect heat transfer of a green roof are: plant height; leaf area index (LAI), which is the leaf area coverage, depending on plant type (typically in the range of 0.5 to 5.0); fractional coverage which measures the portion of the roof surface that is directly covered by at least one leaf; albedo which is the surface's reflectance to incident solar radiation over the plant layer; and the stomatal resistance which is the biophysical variable that controls the rate at which the plant transpires moisture (Sailor, 2008). Simulations in various climates exploring differences in LAI indicate that a high LAI of 5 corresponds to a reduced energy consumption in the summer and an increase in the winter (La Roche & Berardi, 2014).

3.4 Conclusion

The current review aimed to critically analyze a variety of recent peer-reviewed published articles and establish if there is a corroboration of the role of green roofs in the quality of environmental factors. Through thorough evaluation, analysis, and review of case studies, the association between green roof installation, environmental quality, and user thermal comfort is multifactorial and evidentially positive. The critical review explored the possibility of green roof involvement influencing environmental quality to determine whether user thermal comfort is improved. Potential mechanisms representing a causal component of green roofs in user thermal comfort through real-time based and simulation based research include heat flux, carbon dioxide emission, energy consumption, thermal performance, social and aesthetic advantages, habitat biodiversity, air pollution, noise pollution, plant type selection, green roof construction type, stormwater runoff, irrigation system, and maintenance.

Studies and journal articles agreed upon the benefits stemming from green roof implementation, while others had conflicting viewpoints on the same matter. This is largely due to the inconsistency in method design among studies and the varying factors contributing to research outcomes and conclusions.

Upon theoretical framework literature review of real-time and simulation based journal articles, it is evident that there remains a gap in knowledge to the extent of SGR implementation in particular climates, notably hot arid regions. This dissertation objectively aims to provide data analysis and interpretation of combined real-time and simulated collected results to ascertain the degree of a direct link between SGRs on unused rooftops in urban buildings and both building energy consumption and user thermal comfort. This is to determine the principal parameters affected by such installation and their causal sequence. This exhaustive literature review gives a clearer understanding of a holistic approach to include parameters that ought to be studied in this research.

PART 1 CONCLUSION

Taking a holistic approach by situating the concept of green roofs at the center of all facets, establishing a strategy targeting real-time and simulation research has been developed. Chapter 1 has allowed the discovery of a sustainable modular roof system to optimize sustainability in a hot arid region. This includes a light roof structure composed of vegetation, growing medium, drainage layer, filter layer, root barrier, and wireless irrigation IoT automation platform (IRRIOT).

Green roofs have the ability to eliminate and possibly reverse environmental damage (Andric et al., 2020). As has been scientifically proven, the quality of the urban environment can be enhanced in multiple aspects by adopting green roofs in Qatar. Firstly, it may reduce summer cooling energy consumption and costs by increasing heat capacity and providing shading to the bare concrete roof. Secondly, it can improve air quality and cool atmospheric moisture levels. Thirdly, it provides more thermal comfort due to lower ambient temperatures and heat gains from the roof. Fourthly, it can extract CO_2 and contaminants from the air and reduce rainwater runoff (Kumar & Kaushik, 2005; Niachou et al., 2001).

Chapter 2 has identified the lack of digital technology incorporation in green roof design. Through a critical analysis of case studies on green roofs, there is an apparent gap in the association between building energy consumption and user thermal comfort experienced in the building. Furthermore, chapter 3 looks into real-time and simulation based research regarding associations that potentially impact green roofs. These include the aspects of heat flux mitigation, carbon dioxide emission, energy consumption, thermal performance, social and aesthetic advantages, habitat biodiversity, air and noise pollution, plant type selection, green roof construction type, stormwater runoff, irrigation system, and maintenance.

Part 1 is an alleyway focusing on certain aspects to hone into the research methodology development and implementation specifics, which is further elaborated in part 2.

PART 2: RESEARCH METHODOLOGY DEVELOPMENT AND IMPLEMENTATION

PART 2 INTRODUCTION

Part 2 presents the development and implementation of the research methodology for smart green roofs (SGRs), elaborated in Figure 41. Initial layout and description of tools and techniques for using the combined research method are outlined. This lays a path to explore the setup of the experiment. Establishing context, first and foremost, is crucial to dealing with factors that influence the SGRs' use-case.

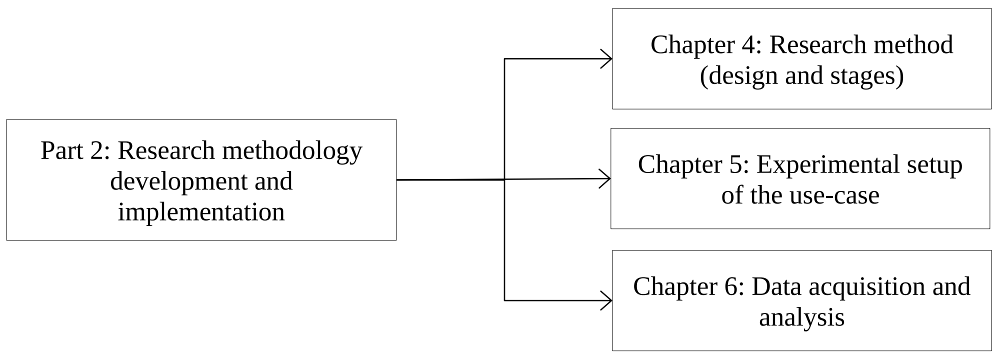


Figure 41. Part 2 research methodology development and implementation.

Outlining the research method in terms of design, stages, and tools, along with strategizing detailed experimental procedures, gives precedence to data acquisition and analysis. Acquiring data meticulously and cautiously is possible with a set-out research method and experimental set-up. Thus, accurate and reliable statistical analysis of such data is conducted through analytical tools through means of an ANOVA test.

CHAPTER 4: RESEARCH METHOD (DESIGN AND STAGES)

4.1 Introduction

This chapter serves as the starting point to direct the research by outlining the design and stages of the method. The goal is to reduce building energy consumption and improve users' thermal comfort via the design, development, and implementation of a smart green roof (SGR) system.

Detailed research methods and tools are set out to measure data in a combined qualitative and quantitative manner. Conducting interviews with a varied number of professionals comprised the qualitative tools used. On the other hand, the quantitative tools used include distributing questionnaires to collect numerical user perspectives and opinions. Furthermore, quantitative tools employed are for real-time and simulation aspects. Following this, calibration of the simulation through DesignBuilder software is discussed.

4.2 Combined Research Methods and Tools

This section looks at the developed framework of the study, including a combined research methodology of qualitative and quantitative tools (Figure 42). The qualitative tools outline the design of interviews administered by an interviewer. In comparison, the stages in the quantitative research aspect include users' questionnaire, real-time experiments, and simulation tools. Quantifiable data were then statistically analyzed through a statistical significance ANOVA test. A combined research tool was used to extract the primary qualitative and quantitative data. The main focus of collecting study data was through the quantitative tool by means of quantifying qualitative data.

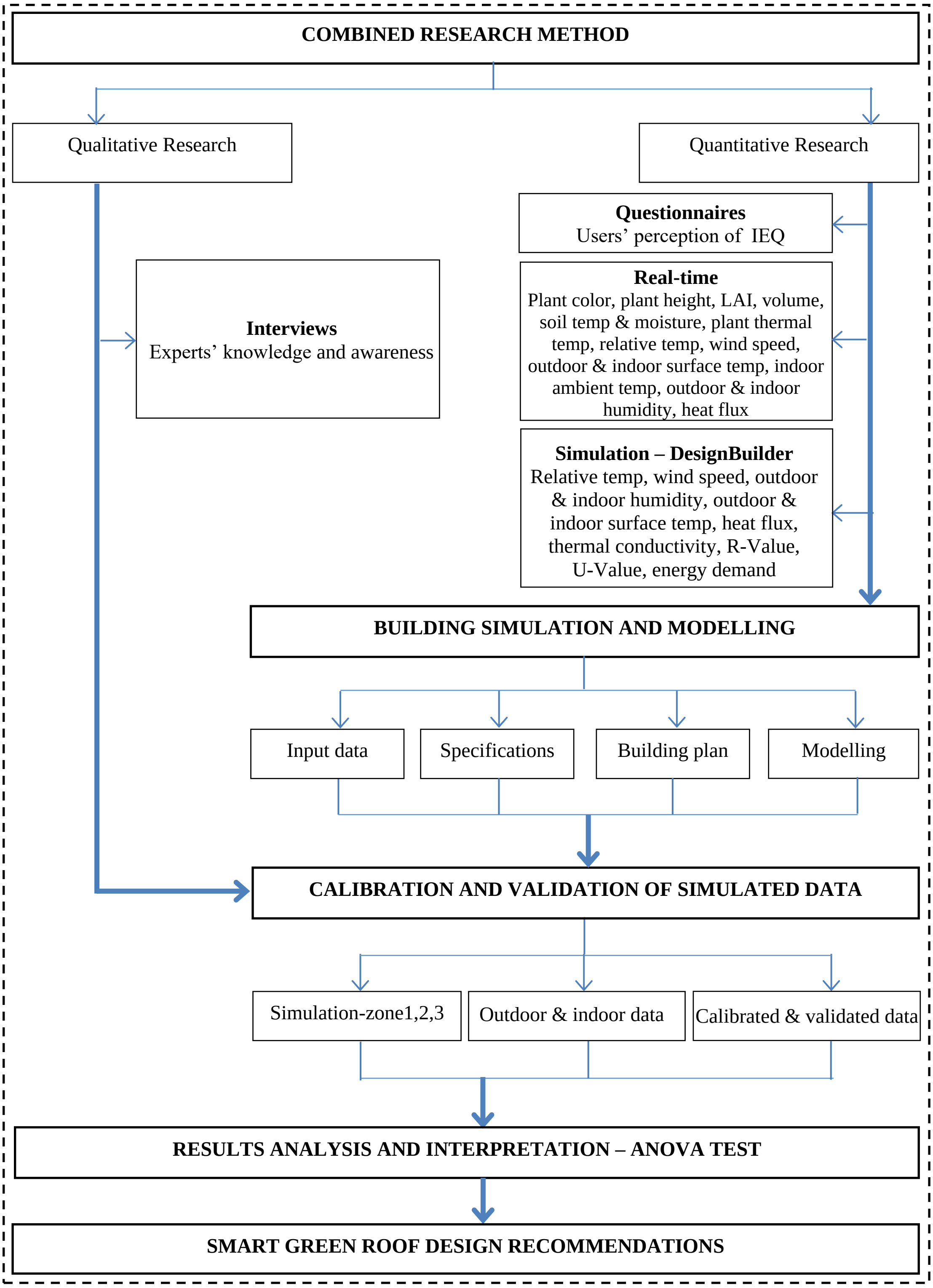


Figure 42. Dissertation framework and research stages flowchart.

Note. IEQ, indoor environmental quality; temp, temperature; LAI, leaf area index; R-Value, thermal resistance; U-Value, overall heat transfer coefficient.

4.2.1 Qualitative Tool

The qualitative tool section provides subjective measurement to obtain better insights into the SGR performance, allowing for both a semi-structured or unstructured and open-ended inquiry. Thus, interviews were conducted with experts in the field to assess knowledge, awareness, and perceptions of SGRs. It captures perceptions and barriers to designing, developing, and implementing an appropriate SGR system that fits within the context of the hot arid region of Qatar. The interviewees comprised 15 field experts, including designers, architects, structural engineers, project managers, and academics.

4.2.2 Quantitative Tool

The quantitative tool yields objective measurements, commonly utilized in many research experiments (Creswell, 2013). Thus, questionnaires were conducted on three existing office building users to examine the quality of the indoor environment. Detailed translation of SGR performance results from measuring users' comfort level. Furthermore, conducting quantitative analysis of visual qualitative data (plant performance), alongside measuring the outdoor and indoor climatic conditions to study objective measurements, engulfed the quantitative tool. This chapter is divided into real-time and simulated-based tools to compare bare and SGRs. Thermal analysis of bare and SGRs was conducted, spanning one year from 01 March 2021 to 28 February 2022, focusing on the peak summer periods (Dabaieh et al., 2015). Real-time data was measured at 30-minute intervals, having real-time and simulated data tabulated hourly, daily, or monthly for analytical purposes. Understanding SGR performance thus determines its effect on the building's thermal and energy consumption in Qatar.

4.2.2.1 Questionnaire Tool

The structured questionnaire approved by the Institutional Review Board (IRB), refer to Appendix A, included close and open-ended questions. Close-ended enquiries were employed to understand the users' comfort level concerning the adaptations involved in the SGR installation. While open-ended questions collected an in-depth understanding of the users' outlook on SGR implementation. The analysis and interpretations of this structured questionnaire generate outcomes that will assist the researcher in proposing efficient recommendations that are valuable, relevant, and applicable to Qatar. The sample size for the questionnaire was 170 respondents, focusing on users of three existing office buildings in Doha.

The questionnaire will aid in understanding the users' perception and thermal comfort to assess the building's indoor environment quality (IEQ). Thermal comfort is characterized by the users' satisfaction with the thermal environment (GSAS Building Typologies, 2019). In warm climates, perspiration and hyperthermia, in extreme cases, may ensue, whereas cold environments may substantially lead to a drop in body temperature. The level of user satisfaction is assessed through a questionnaire using the ASHRAE thermal sensation scale and the predicted mean vote (PMV) scale, illustrated in Figure 43. There has been a large debate about the accuracy of PMV as a tool to measure users' thermal comfort, with overestimations at the extremes of the model and the accuracy of predictions at 34% (Alfano et al., 2020; Cheung et al., 2019). Although this is the case, the PMV scale is only one means to quantify users' comfort.

To comply with ASHRAE 55-2010, the suggested thermal limit on the PMV 7-point scale is between -0.5 and 0.5. This limit is expanded upon by ISO 7730, which provides different indoor environment ranges. The hard limit, according to ISO, is between -2 and +2: for existing buildings, it is between -0.7 and +0.7, and for new construction, it is between -0.5 and +0.5 (Guenther, 2021). The second thermal model used is the adaptive comfort model, which consists of physiological, behavioral, and psychological adaptation (Yau & Chew, 2014). The inputs for PMV and the adaptive comfort model include building relative humidity, wind velocity, air temperature, rate of metabolism (activity), and clothing (heat loss rate), calculated according to the questionnaire.

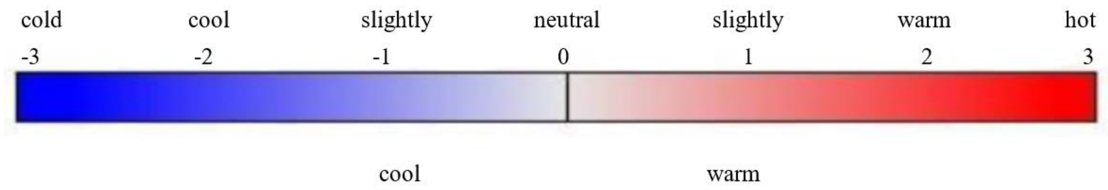


Figure 43. ASHRAE thermal sensation scale and predicted mean vote scale (Source: ANSI/ASHRAE Standard 55-2010).

Moreover, the approximate clothing and thermal insulation (clo) values were calculated according to the responses in accordance with ANSI/ASHRAE Standard 55-2010 and Figure 44. Users' can comfortably adapt to the thermal environment by adjusting their attire (Moreno et al., 2008). To conclude, the questionnaire was designed to consist of background information about users and their occupation in the building, the users' general room perception, their comfort, the strategies used to adapt to the environment, and users' awareness of SGRs (refer to Appendix B).

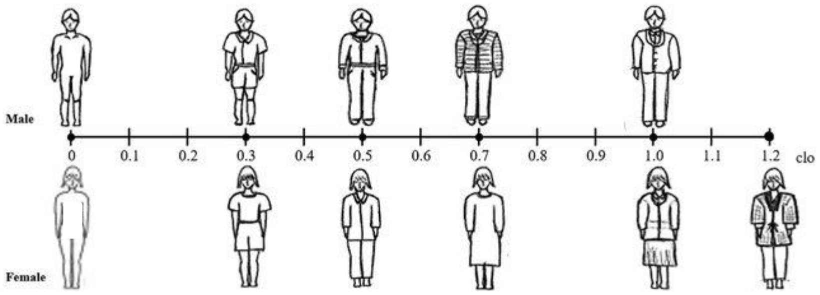


Figure 44. Clothing and thermal insulation (clo) units of different clothing items (Source: Rijal et al., 2019).

4.2.2.2 Real-Time Tools and Techniques

Visual observational techniques were employed to identify and measure SGR performance, thereby, energy performance. Visual observations of plant color, plant height, leaf area index (LAI), and smart irrigation system layout were noted (Figure 45). The visualization technique is a holistic approach to observing the plants' performance, growth, and development without harming them in the process. This section also consists of tools regarding temperature, humidity, wind speed, and heat flux measurements. It is, therefore, of great importance to reduce heat flux through the roof and improve building energy performance following the implementation of a well-performing SGR system.

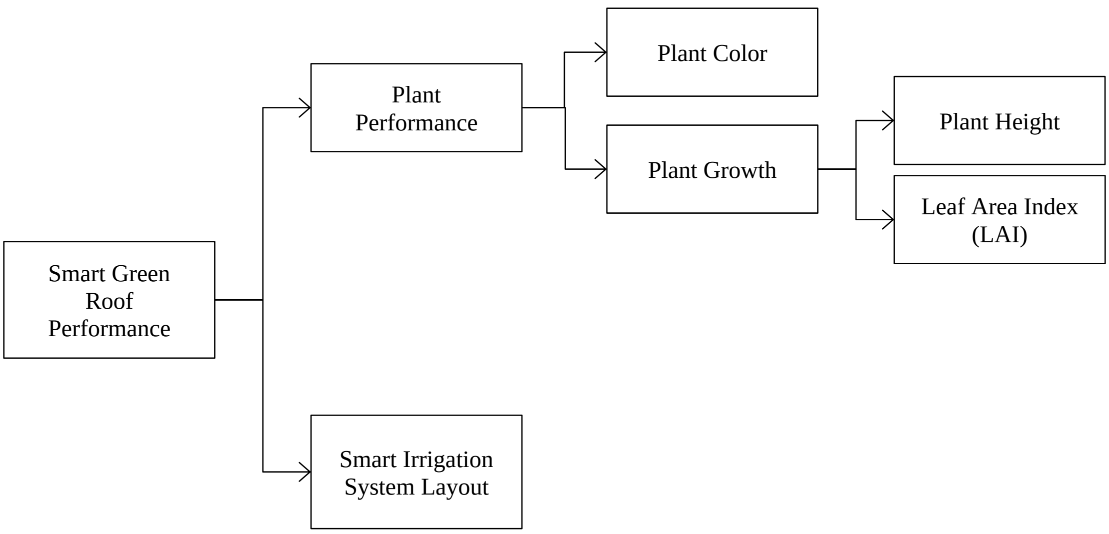


Figure 45. Smart green roof performance criteria.

Plant color is an observational technique that includes studying color changes over time. Plant pigments can help determine and understand plants' performance, condition, photosynthesis, growth, and development. The protective UV pigment becomes dull and damaged when unsuitable plants meet total sun exposure with inappropriate soil nutrients. Thus, recording the color changes help attain an improved operational and well-performing SGR system (Garcia-Vaquero & Rajauria, 2018). Communicating semantics to distinguish the plant conditions is needed to record the color quality better. Conklin (1955) developed a color classification that provides visual stimuli. This classification system has been adapted to suit the research experiment for use with Qatar's local plants to identify plants' conditions. The adapted color classification tool is explained in Table 24 with categorizations of classification, code, color range, and plant condition. The color code ranges from 1-4, 1 being the poorest plant condition, and 4 being the highest plant performance based on color.

Table 24. Numerical color classification of local plants (Adapted from: Conklin, 1955)

Classification	Code	Color Range	Plant Condition
Plant color	**1**	White and very light tints of other colors and mixtures	Dryness or desiccation
	2	Light green and mixtures of green, yellow, and light brown	Light; pale, weak, faded, or bleached
	3	Green, maroon, red, orange, yellow, and mixtures in which these qualities are seen to predominate	Dark
	4	Black, violet, indigo, blue, dark green, dark gray, and deep shades of other colors and mixtures	Wetness or freshness; deep, unfading, or indelible

In terms of plant height and LAI, SGR performance is also determined by plant growth. Regarding plant height, the growth is vertically measured; for LAI, the plant growth is measured horizontally. Plant height is measured from the border of the pod to the top of the plant stem in centimeters (cm). It is important to note that identifying the pod's border may be imprecise due to the swelling of the soil moisture from constant watering, resulting in inaccurate plant height values (Measuring Plant Growth, 2018).

Through indirect visual means, the LAI values were quantified. This indirect technique is suitable for collecting LAI measurements, as it is less time-consuming and avoids destroying the leaves (Campbell, 2021). Visually calculating LAI to a set of base photographs by Susorova (2013) was used to assess plant growth. LAI of ~0.25 to ~1.5 is depicted in Figure 46, where an LAI of ~0.25 signifies fewer leaf area coverage and lower density, an LAI of ~0.75 indicates medium density, and a ~1.5 LAI denotes dense leaf area coverage.

Figure 46. Set of base photographs to determine leaf area index values based on leaf coverage (Source: Susorova, 2013).

Plant performance in terms of color and LAI was, at times, remotely monitored through a HikVision PTZ camera. The camera is mounted onto the building's wall by a bracket Hik white Aluminum alloy at a height of 2.6m (Figure 47). The surveillance camera can be accessed via the iVMS-4200 3.5.0.7 client application on a personal computer or via the Hik-Connect mobile application (Figure 48). The HikVision PTZ surveillance camera was situated at its respective height as the penthouse roof structure provided some shading and protection from the solar and ambient heat (Karachaliou et al., 2016). The camera also had a function for 360° vision. Thus, this functionality was not hindered at the height of 2.6m and had the most appropriate view of the SGR.

Figure 47. Position of the surveillance camera.

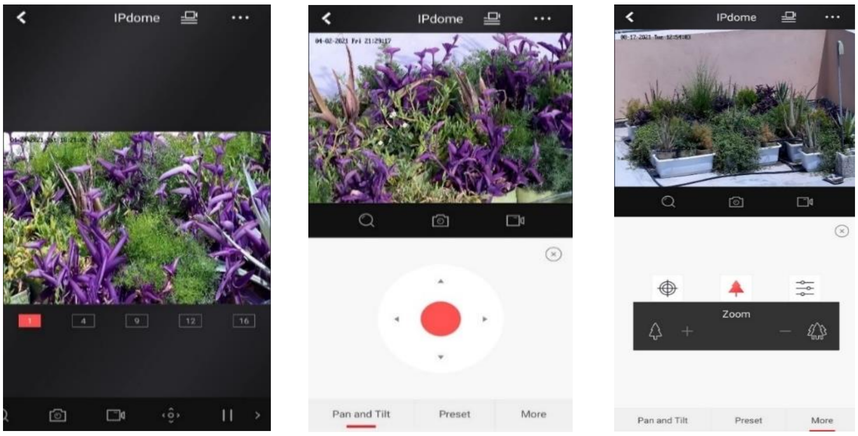


Figure 48. Hik-Connect mobile application for the surveillance camera.

Several observations of plant types, material, and smart irrigation system layout were explored to investigate the extent of the SGR performance. Visual monitoring of plant viability, vigoroot geotextile wicking fabric, irrigation capacity, and its effects, drainage system layout, and pipeline system layout were determinants of plant performance in SGRs in Qatar’s hot arid climate. Analysis of the impact these determinants have on the energy performance of the building can be carried out by quantifying the data obtained from qualitative observational research.

In the case of Doha's hot, dry climate with extreme heat, significant changes between day and nighttime temperatures are pronounced in this hot arid environment (Dahl, 2010). For bare and SGRs, the following parameters were measured and compared using loggers and sensors: outdoor air temperature and humidity at 1m, outdoor relative temperature, outdoor wind speed, indoor surface temperature of the ceiling, indoor ambient temperature, indoor humidity, and heat flux. In contrast, the soil moisture, soil temperature, and plants' thermal temperature were only measured for the SGR.

The installed thermal monitoring system acquired data from the sensors in the experimental building, recording the measured data through a cloud computer system accessible with an internet connection. The sensors and data loggers monitoring the SGR thermal performance were installed indoors and outdoors in the building.

The EM300-TH Milesight sensor connected to the UG65 LoRaWAN gateway recorded data at 30-minute intervals, measuring outdoor air temperature and humidity at 1m for both green and bare roofs (Figure 49). The sensors were also attached to the ceiling level inside rooms 10A and 10B, measuring indoor surface temperature, ambient temperature, and humidity for green and bare roofs (Figure 50).

Figure 49. UG65-L00E-868M-EA LoRaWAN gateway.

The GRAPHTECH GL240 logger measured heat flux, shown in Figure 50. On the other hand, soil moisture and soil temperature were measured using the BGT-SM1 sensor. Moreover, the soil moisture sensor is essential for calculating data for the drip irrigation system. It is directly communicated to the IoT hub through the IRRIOT remote controller, with specifications listed in Table 25.

Figure 50. GRAPHTECH GL240, BGT-SM1, and EM300-TH temperature and humidity sensors.

Table 25. Remote unit specification (Adapted from: Wireless Precision Irrigation Internet of Things Platform, 2019)

Radio Technology	LoRa, ISM radio band (License Free)
Outdoor Connectors	2 x 2pin, 1 x 4 pin, 1 x MicroUSB (IP67)
Dimensions (without connectors)	91 wide x 112 high x 78mm deep
Rechargeable Battery	Size 18650 Li-Ion (no replacement needed)
Antenna	Indoor/Outdoor
Operating Temperature	-30°C to +60°C
Supported solenoids	9VDC Latching Solenoids (Hunter®, Toro®, etc.)
Supported sensors	Irrometer® Watermark Soil Moisture sensor or any sensor switch
Mounting Options	Pole, Fence, Wall
Waterproof IP rating	IP67 Vented
Solar panel	Integrated solar cell

Note. LoRa, long-range; ISM, industrial, scientific, and medical; IP, ingress protection; VDC, solenoids valve; mm, millimeter; and °C, degrees Celsius.

This wireless irrigation controller consists of a base unit, as shown in Figure 51, and a remote wireless valve control station, as shown in Figure 52. The IRRIOT controller is accessible through a computer-based application, illustrated in Figure 53. Measuring the water volume is less common in the IRRIOT system, being an auxiliary function; thus, a manual calculation was employed. The water volume consumed was determined through a formula, multiplying the flow rate by the irrigation duration, shown in Figure 54. It must be noted that this formula was unsuitable for calculating water volume consumption during manual irrigation in phase 1 of the experiment, which is further explained in section 5.5.2.

Figure 51. Base unit of IRRIOT system.

Figure 52. Remote wireless valve control station of IRRIOT system.

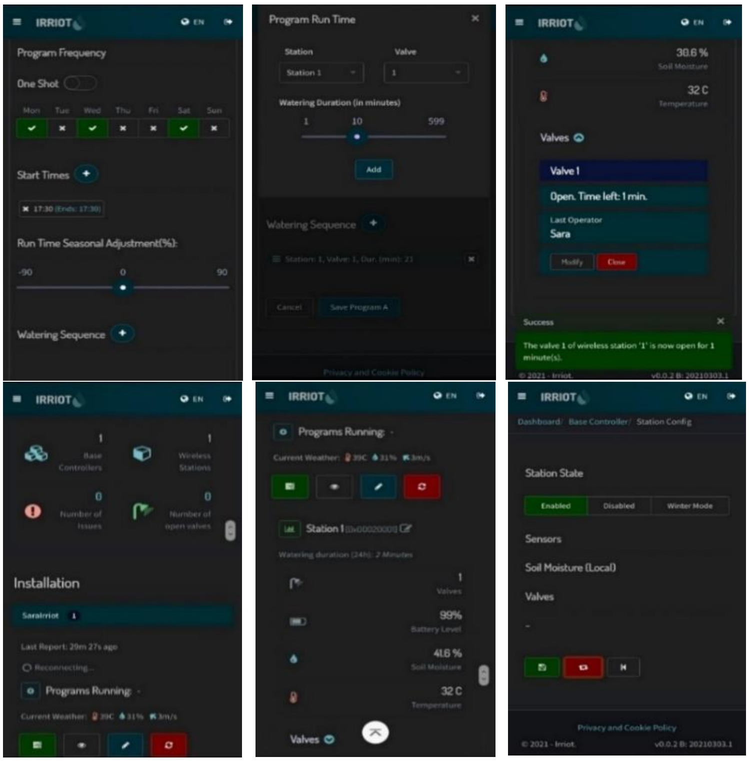


Figure 53. IRRIOT computer-based application.

$$V = t \times Q$$

Figure 54. Calculation of water volume consumption (Source: Khan Academy, 2022b).

Note. V is the volume, t is watering duration in hours, and Q is the volume flow rate.

The meteorological parameters (relative air temperature, relative humidity, and wind speed) and Doha weather data were obtained using the IRRIOT computer application. The indoor and outdoor measurement locations in the building are shown in Figure 55, 56, and 57. The indoor temperatures and indoor humidity were measured in a characteristic office room on the upper floor of the building. In comparison, the outdoor equipment was placed in protective cases to protect them against the sun's rays and heat (Karachaliou et al., 2016).

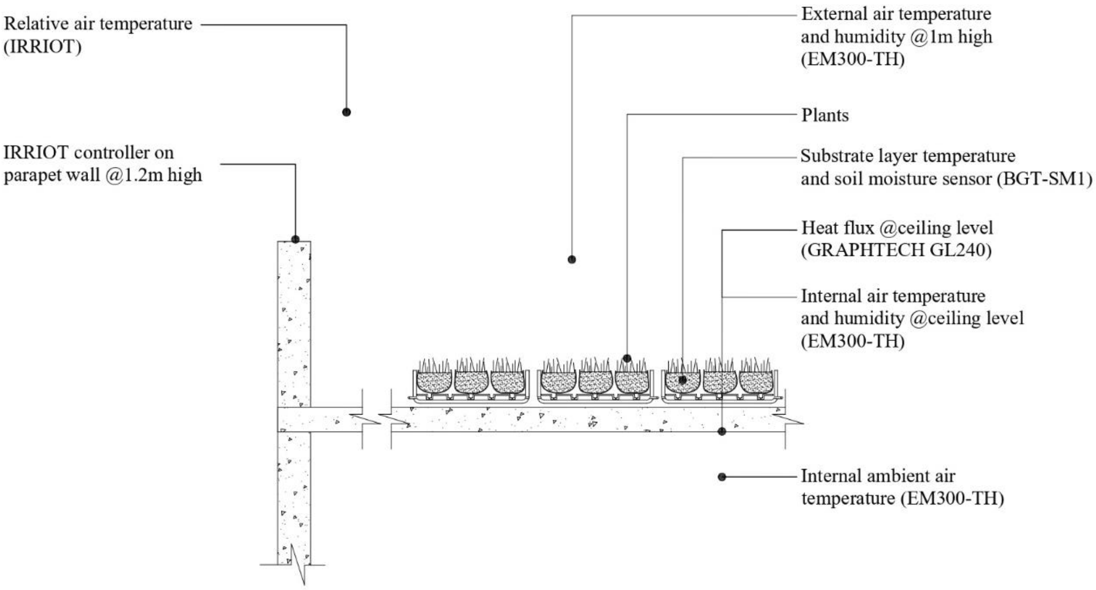


Figure 55. Section of smart green roof measurement locations.

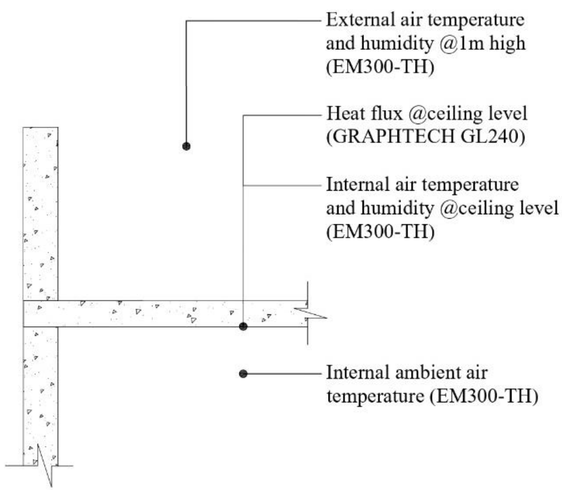


Figure 56. Section of bare roof measurement locations.

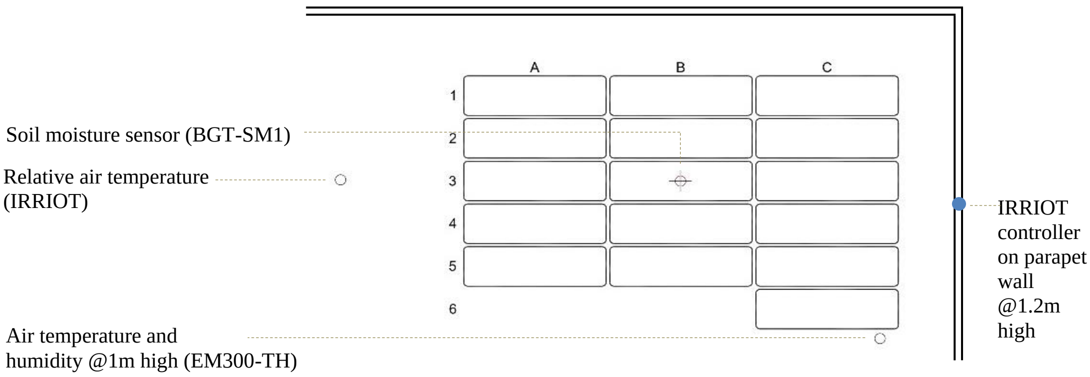


Figure 57. Plan of smart green roof measurement locations.

Infrared camera thermography measurements, obtained via E40 FLIR, were also taken to record the plants' leaf thermal temperature. The camera is set on an iron palate composed of violet and yellow color spectrums in this experiment. The former color code indicates lower heat consumption, and the latter color signifies increased assimilation from the environmental heat. Thus, measuring plants' thermal heat absorption determines plant operation in SGR performance.

A detailed summary of instruments, and their specifications, used to record real-time data is presented in Table 26. Accordingly, the location and quantity of these instruments are ascertained in Table 27.

Table 26. Instruments, parameters, and specifications

Make	Device Model	Parameters	Device Type	Specifications
Milesight IoT **Cloud computer-based (provides unparalleled levels of vertical integration betwee n the sensors and Milesight LoRaWAN)** **Data is collected at 30min intervals**	**EM300-TH**	-Outdoor temperature -Indoor surface temperature -Indoor ambient temperature -Outdoor and indoor relative humidity	Wireless sensors	-IP67 Waterproof. -NFC enabled -LoRaWAN® Wireless. -5/10 Years Battery Life. -1 * 4000 mAh Li-SOCL2 battery (8000 mAh optional) -Temperature accuracy 0~70°C: ±0.3°C -30~0°C: ±0.6°C -Temperature resolution 0.1°C -Humidity accuracy ±3% (10~90%RH) ±5% (Other ranges) -Humidity resolution 0.10%
	UG65-L00E-868M-EA	Collects the data sent from sensors and then transmits the data to the cloud	LoRaWAN Gateway	-IP65 rated -8-CH -Wi-Fi -PoE -1 * 10/100/1000Mbps (1 * WAN) -Built-in Network Server -Cellular (2G & 3G & 4G)
Soil moisture sensor	**BGT-SM1**	-Soil moisture -Soil temperature	Compatible sensor with the IRRIOT controller	-Range:-30~70ºC; 0~100% -Probe length: 5.5cm -Probe diameter: 3mm -Probe material: Stainless steel 304 -Sealing material: Epoxy resin -Accuracy: ±3%;±0.2ºC -Measured stability time: 2s -Response time: <1s -Measuring frequency: 100MHz
GRAPHTEC	**GL240**	-Surface temperature -Surface humidity	Midi logger	-Accuracy ± 0.1% of the full scale
Hukseflux	**HFPO1**	-Heat flux	Thermal sensor	-Accuracy ± 5% of reading (W/m^2) -IP67 -Measurement range -2000 to +2000 W/m^2
IRRIOT (IRRigation Internet of Things) **Cloud-based (compatible with Microsoft Azure for remote monitoring)** **Data is collected at a 1hr interval**	**Controller and base unit (solar-powered with battery-free smart irrigation)**	Obtained data using the IRRIOT application: -Soil moisture -Soil temperature -Relative temperature -Relative humidity -Wind speed	Wireless irrigation controller	-Suitable for rooftop gardens. -A set of push buttons and a display are included in the base unit (controller), which can configure watering in various ways. -The base unit is 24/7 in charge of executing a preconfigured watering schedule, monitoring the soil's condition, responding to failures, etc. -The Microsoft Azure IoT Hub is connected to an IoT device known as the base unit (controller). -34 or more sensors (e.g., soil moisture or rain sensors). -IRRIOTs application allows full control and remote monitoring of the irrigation at any time and location. -Support for third-party cloud-based sensors (pressure, flow, temperature). -Wireless valves/sensors two-way communication is the primary distinction between the IRRIOT Wireless Irrigation Controller and the classical controller. In practice, IRRIOT introduces a wireless valve positioned remotely.

Make	Device Model	Parameters	Device Type	Specifications
HikVision	**PTZ camera**	-Video recordings -Remote playback	CCTV surveillance camera	-MP 15x Dark fighter low light IP, 120dB WDR, IP66, up to 100m IR -360 degrees motion -Zoom in-out function (15xoptical zoom, 16xdigital zoom, focus: auto/ semi auto/ manual) -Support Micro SD/SDHC/SDXC, up to 256 GB -Can be connected to up to 4 devices -Recording can be accessed from PC (iVMS-4200 3.5.0.7 Client application) or mobile (Hik-Connect application) through remote playback -Video streaming -Day and night mode -4CH PoE NVR with 1 SATA interface, four built-in- PoE Ports, recording up to 8MP, 1HDMI output up to 4k
E40 FLIR	**FLIR Exx series camera**	-Thermal plant temperature	Thermal camera	-Features a 160 x 120 60Hz infrared detector with a 0.07°C thermal sensitivity and a -20 to 650°C (-4 to 1202°F) temperature range

Table 27. Location and quantity of instruments

Location	Roof Type	Device Installed	QTY.
Outdoor (roof level)	**Green and Bare Roofs**	EM300-TH Temp/RH sensor BGT-SM1 soil Moist/Temp sensor IRRIOT controller and base unit	2 1 1
Indoor (first floor)	**Green and Bare Roofs**	UG65-L00E-868M-EA LoRaWAN gateway EM300-TH Temp/RH sensor GRAPHTECH GL240 logger HFPO1 Heat flux sensor	1 4 2 2
Outdoor	**Not Specific**	Surveillance camera	1
Outdoor and Indoor	**Not Specific**	Thermal camera	1

4.2.2.3 Simulation Tool

DesignBuilder software is the simulation tool used to generate simulated data outputs. A quantitative building energy computation simulation tool is efficient, effective, and economical in obtaining profound descriptions and understandings of energy consumption and performance data (Usman et al., 2021). In comparison, real-time physical modeling leads to accurate results, but it is time-consuming and requires energy, money, and many facilities. However, it is needed because it creates precise measurements. Since it is difficult to physically examine the existing building conditions of the green and bare roofs, DesignBuilder software becomes an effective alternative because of its reliability, ease of changing environmental factors, and reproducibility.

DesignBuilder V.7.0.0.102 software package provides a Graphic User Interface (GUI) to the most comprehensive and effective user interface and energy simulation engine for EnergyPlus. It is used in this research to address SGR design, capable of modeling parametric and performance-based graphical outputs. The software allows the creation of various building geometry and parameterized parameters, such as the activity type, occupancy rate, environment control, indoor loads, construction types, opening types, material selection, lighting, HVAC systems, and Computational Fluid Dynamics. The energy simulation software further inputs green roof parameters, including plant height, stomata conductance, growing media depth, LAI, thermal bulk properties of soil, and soil moisture conditions through irrigation. Through simulation tools, this study investigated heat transfer and thermal performance in Qatar across a bare roof and an SGR to understand better the effect of SGR parameters on a building's energy consumption.

A base case roof model will be developed for the office building using DesignBuilder for three zones, being ground floor (zone 1), first floor (zone 2), and penthouse (zone 3). The Meteonorm software package provided the meteorological data used as an EnergyPlus Weather File, which was inputted into DesignBuilder as a location file. The study also identified a software configuration that enabled a digital workflow, as shown in Figure 58.

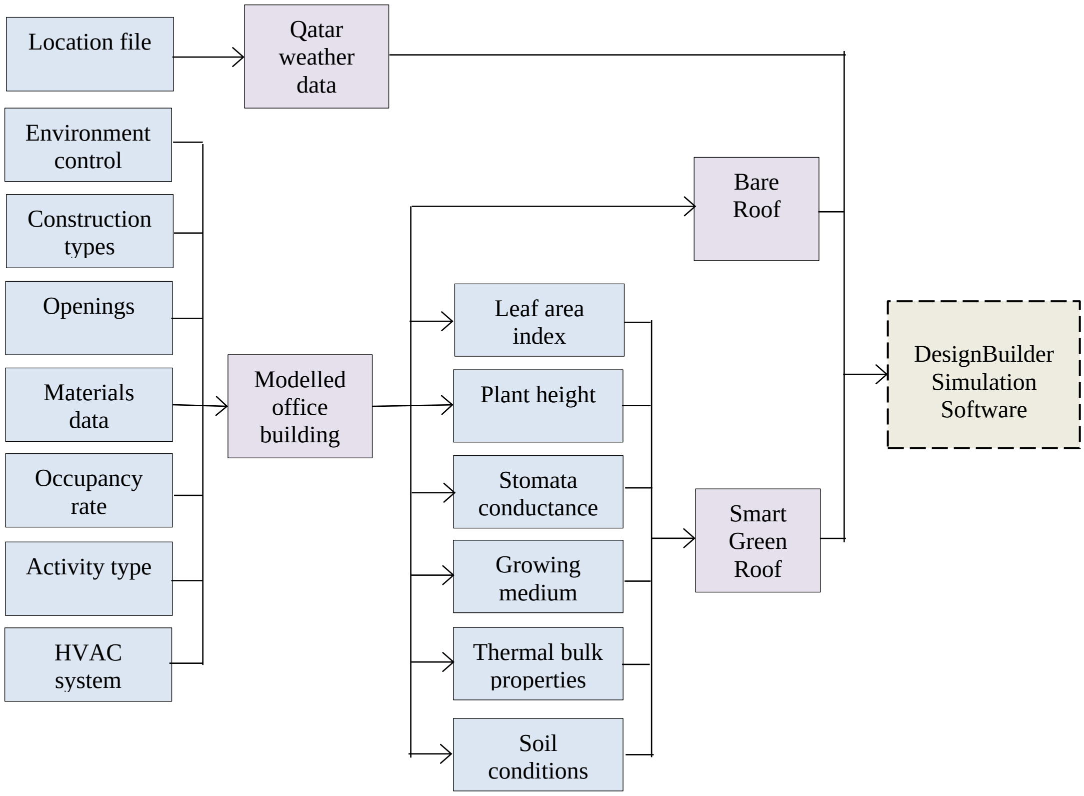


Figure 58. Workflow of data acquisition and analysis.

The material's thermal properties must be better understood to annotate thermal design considerations. The inputted data of DesignBuilder resulted in a simulation of extracted data to conduct studies on thermal conductivity, thermal resistance (R-Value), overall heat transfer coefficient (U-Value), heat flux, outdoor relative temperature, outdoor wind speed, outdoor relative humidity, indoor surface temperature, and energy consumption of the total sum of sensible cooling required. With a focus on the simulated peak relative temperature and heat flux throughout the year, assessing the 24-hour data of real-time zone 2 outdoor temperature at 1 meter above the roof surface and simulated data for three parameters in zones 1, 2, and 3, for both bare and SGRs: indoor surface temperature, heat flux, and energy consumption of the cooling required. Considering thermal design parameters aims to optimize energy consumption for environmental, social, and economic aspects.

The properties that measure the thermal characteristics of building material simulated through the DesignBuilder software are thermal resistance (R-Value) and overall heat transfer coefficient (U-Value). The study adopts the thermal conductivity equation, as it cannot be derived from DesignBuilder. However, the simulation tool generated data outputs for variables that calculate thermal conductivity.

Thermal conductivity measures a material's ability to conduct heat; it is the rate at which heat is transferred through the material, perpendicular to the surface of one square meter area of the material. Thermal conductivity is affected by the density and moisture of the materials and ambient temperature. If materials density, moisture, and ambient temperature increase, the thermal conductivity also increases (Alvarez-Guerrero et al., 2022; Determination of Thermal Conductivity, 2010). A higher thermal conductivity (W/mK) rate means high heat transfer compared to materials of lower thermal conductivity. The following formula below (Figure 59) shows the equation to calculate the construction material's conductivity.

$$k = \frac{\Delta Q}{A \times \Delta t} \times \frac{x}{\Delta T}$$

Figure 59. Thermal conductivity formula (Source: Khan Academy, 2022a).

Note. k, thermal conductivity; ΔQ, change of quantity of heat; A, total cross-sectional area of conducting surface; Δt, change of time duration for heat transferring; x, thickness of conducting surface; and ΔT, temperature difference of conducting surface.

The reciprocal of thermal conductivity is thermal resistance. Thermal resistance is the heat transfer resistance through a given material thickness. The higher the R-value (m^2K/W), the more thermal resistance the material of heat to transfer and, thus, better insulation (Green Age, 2021).

The overall heat transfer coefficient measures how much heat is lost in a material. The lower amount of heat loss, the lower the U-value (W/m^{2}K), associated with higher insulative properties (R-Value), and vice versa (Figure 60). The U-value, thus, helps determine a material's insulative properties. The higher the insulator (R-Value), the less heat transfer between objects and the more effective it is for Qatar's hot and arid climate. Although U-value properties are not mandatory in the building codes of Qatar, they can be a great addition to appropriately selecting a material heat insulator.

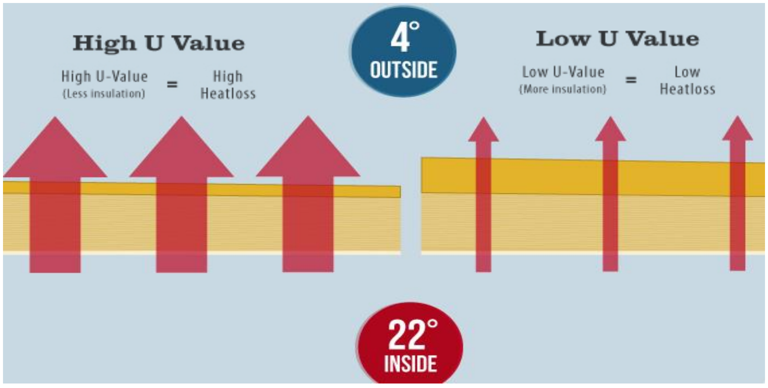


Figure 60. Thermal conductivity, U-Value, and R-Value relationships (Source: Green Age, 2021).

4.2.2.4 Calibration of the Simulation Tool

As highlighted by Polo-Labarrios et al. (2020), an emphasis on the importance of research studies related to the modelling of heat transfer through green roofs carries a comparison study of the measured data against the modelling tool. However, there is a lack of this comparison in hot arid regions. For that reason, the measured data results are used to calibrate the model's study by comparing the measured values and the predicted values of the DesignBuilder V.7.0.0.102 software package.

The simulated model was calibrated using data derived from real-time data of the office building during a single year, from 1 March 2021 to 28 February 2022, with a focus on peak summer periods. The simulation tool was calibrated by comparing the real-time data with the simulated data to generate a reliable simulation model and verify the base case model. A comparison of real-time weather and DesignBuilder simulated weather, according to Qatar Meteorological Department, was achieved. The weather data of site-specific outdoor and indoor parameters was compared daily. The calibration tool used included a variety of steps according to ASHRAE Standards 140-2017 and previously published studies (Mahar et al., 2019; Semahi et al., 2020). Three ASHRAE Standards indices were applied for the manual calibration of the building simulation model, including (1) mean bias error (MBE), (2) coefficient of variation of root mean square error [CV(RMSE)], and (3) coefficient of determination (R2). The following equations presented below were used to calculate the MBE, CV(RMSE), and R2 values (Figures 61, 62, and 63).

$$\text{MBE} = \frac{\sum_{i=1}^{Np}(Mi - Si)}{\sum_{i=1}^{NP} Mi}\ (\%)$$

Figure 61. Mean bias error (Source: Mahar et al., 2019; ASHRAE Standards 140-2017).

Note. MBE, mean bias error; Mi and Si, measured and simulated data at a time interval; I and Np, total number of data values used for the calculation, %, percent.

$$\text{CV(RMSE)} = \frac{1}{M}\sqrt{\frac{\sum_{i=1}^{Np}(Mi-Si)^2}{Np}}\ (\%)$$

Figure 62. Coefficient of variation of root mean square error (Source: Mahar et al., 2019; ASHRAE Standards 140-2017).

Note. CV(RMSE), coefficient of variation of root mean square error; Mi and Si, measured and simulated data at a time interval; I and Np, total number of data values used for the calculation; %, percent.

$$\text{R2} = \frac{SSreg}{SStot}$$

Figure 63. Coefficient of determination (Source: Semahi et al., 2020; ASHRAE Standards 140-2017).

Note. R2, coefficient of determination; SSreg, measured explained variations; SStot, measured total variation.

According to ASHRAE Standards 140 criteria, the simulated model is considered calibrated if:

- Daily MBE values are within $\pm$7.5%, and daily CV(RMSE) values are below 22.5%
- The coefficient of determination should be R2 $\geq$ 0.75

4.3 Conclusion

Chapter 4 explains and clarifies the research methodology adopted. It has also presented its design and stages to explain the tools and techniques used in this combined research methodology. This chapter began by introducing the tools employed to address the SGR's design, development, and implementation aspects. Qualitative and quantitative variables were recorded by providing a detailed overview of the means for raw data acquisition. These methods and tools are used to understand the role and performance of SGRs concerning energy demands and the user’s thermal comfort level.

A targeted design for interview formulation and distribution to study participants encompasses qualitative tools. Through interview means, responses from experts in the field of green roofs were gathered. Moreover, questionnaire data of user responses were quantified. Primarily, the predicted mean vote scale and clothing (clo) units were used to establish users’ comfort in their thermal environment. From a quantitative perspective, visual observations are quantifiable using an adapted numerical color classification system for Qatar's local plants to understand SGR performance and its corresponding effect on building energy consumption.

Furthermore, quantitative real-time and simulation based tools encompassed measurements for temperature, humidity, wind speed, and heat flux, with the use of sensors, loggers, thermal imaging, a surveillance camera, an IoT computer hub, and DesignBuilder software tool. The measurement equipment allows for remote collection of and command to the SGR. This combined study approach was used to calibrate the DesignBuilder simulation data against real-time data. Further explanations of the manual calibration of the simulation software tool following three indices of the ASHRAE Standards were given.

The purpose of this chapter is to assist in exploring a balanced solution between the user’s thermal comfort and the building's energy consumption. A precise image of the use-case, including site area, climate, building envelope information, and SGR type, structure, and smart irrigation system for the office building, will be further discussed in the next chapter.

This thesis will present the first in-depth investigation of SGR implementation, building energy consumption, and user thermal comfort. In addition, it describes the different methodological strategies to acquire qualitative and quantitative data through a combined research approach. The following chapter examines the experimental research layout in more detail and proposes a smart irrigation system.

CHAPTER 5: EXPERIMENTAL SETUP OF THE USE-CASE

5.1 Introduction

A significant proportion of environmental and user benefits are derived from implementing smart green roofs (SGRs) to existing buildings in an urban hot arid climate. Increased building energy consumption is causing major environmental degradation consequences. This is exemplified by their associated diminishing effects on user thermal comfort in a building in an urban landscape. Therefore, there is currently a necessity to design and implement novel natural alternatives (SGRs) to help alleviate this problem.

This chapter presents the use-case study of the design, development, and implementation of an SGR in existing buildings in the hot arid climate of Doha, Qatar. It is inclusive of Qatar meteorological data, study area, selection criteria and justification, building envelope, Qatar SGR application use-case, and conclusion. The use-case allows understanding of the research context in a more comprehensive and detailed manner, specific to a hot arid dry climate.

5.2 Qatar Meteorological Data

Qatar is in the Middle East region of Asia at latitude 25.25N, longitude 51.57E, and an elevation of 10m above sea level, as shown in Figure 64 (Maps of world, 2021). The climate is characterized by the hot desert (BWh Köppen climate classification; 1B very hot-dry ASHRAE climate zone) (Pernigotto & Gasparella, 2018). The hottest season occurs throughout the May to October months. Doha has dry periods ranging throughout the year in all 12 months. The warmest month is July, with a maximum temperature of 41.5°C. Humidity is usually the lowest from May to June (Figure 65). Natural renewable water resources such as the ground and rainfall water are rare.

Rainfall is 75mm per annum, mainly between October to March (Clima Temps, 2021).

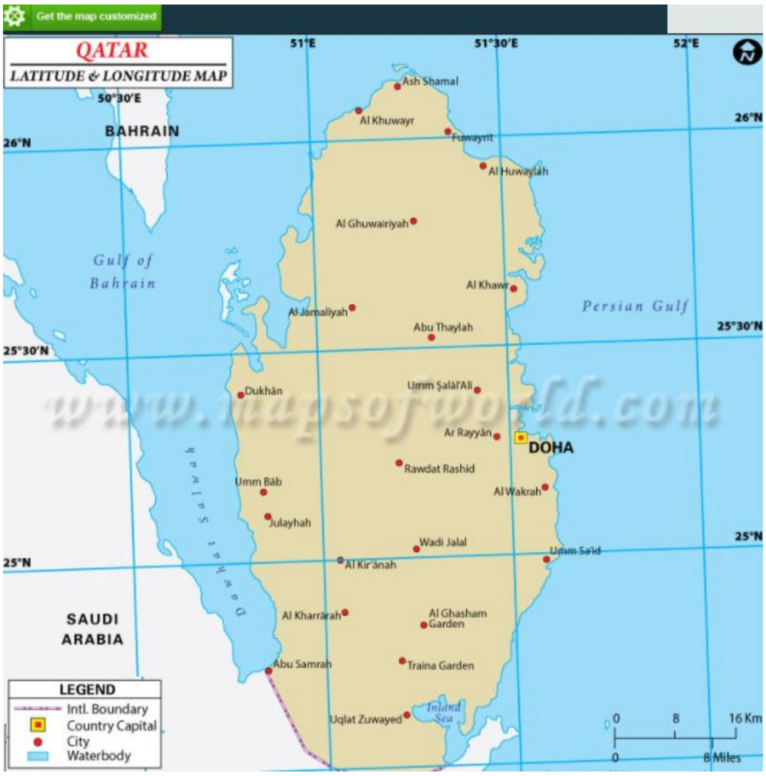


Figure 64. Qatar Latitude and Longitude Map (Map source: Maps of world, 2021).

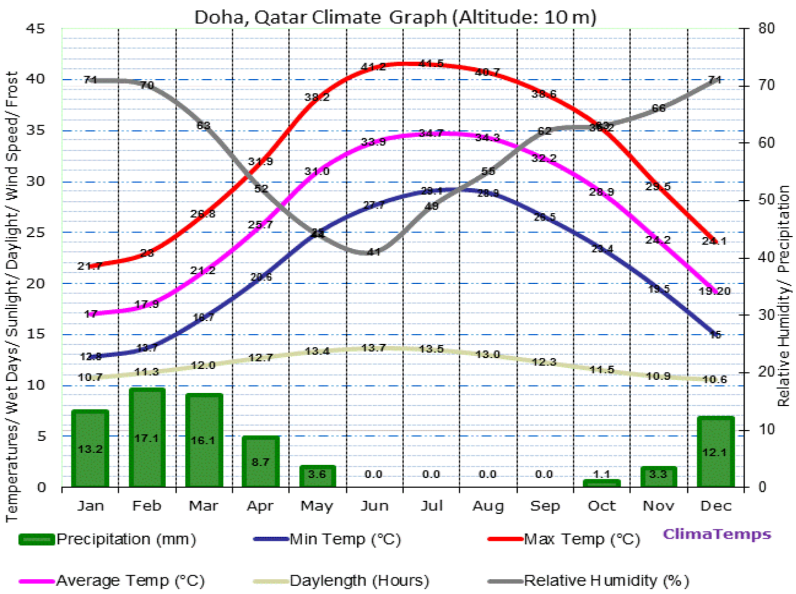


Figure 65. Monthly weather characteristics for Qatar for the last ten years – 2010 to 2020 (Source: Clima Temps, 2021).

5.3 Study Area, Selection Criteria, and Justification

The research study aims to design, develop, and implement SGRs in the urban environment of Doha through a research-oriented approach. This targets to enhance user comfort and improve the energy efficiency of the building. The use-case is an office low-rise building located in Doha, Qatar (Figure 66).

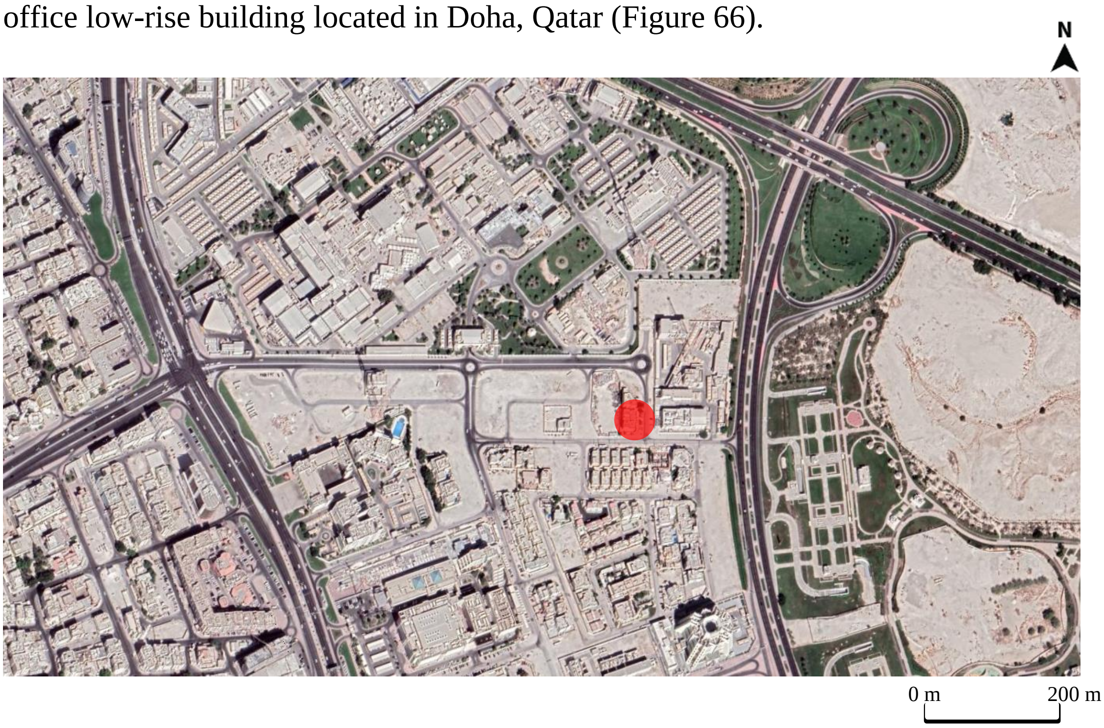


Figure 66. Office building: location plan of the experimental study area.

An office building was selected as the use-case to undertake the SGR study. The reported findings of the SGR applied to an urban office building shall: prove environmental benefits (Ziogou et al., 2018), supply improved thermal comfort (Erdemir & Ayata, 2017), and show efficiency in reducing energy consumption (Ragab & Abdelrady, 2020; Ziogou et al., 2017) because of the reduction of the building's cooling load during peak summer (Haggag et al., 2014; Spala et al., 2008). The dissertation should be a hallmark to entice legislative changes made in favor of SGRs (Mohamed et al., 2019; Tassicker et al., 2016). This is to advance the growing urban industry towards SGR implementation in the hot arid climate of Qatar.

The chosen period for the experimentation is one year, starting from March 2021 and concluding in February 2022. Measurements are taken of the use-case elements during this one-year period. In hot and arid climates, smart green roofs may be exposed to extreme temperatures and UV radiation, which can place additional stress on the roof and the plants. The effectiveness of a smart green roof in hot and arid climates can be assessed by monitoring roof and plant conditions over time to ensure that they can withstand climatic conditions. Rayner et al. (2016) study the durability of plants on an extensive green roof under extreme hot and dry conditions over 42 weeks, noting the leaf succulence's importance in plant selection.

To experimentally determine the effect of SGRs on buildings' thermal performance, an SGR is to be compared against a bare roof, both roofs placed on the South orientation of the office building use-case. Temperature distributions within the building are greatly affected by the green roof's orientation (Alexandri & Jones, 2008). Despite this, the amount of vegetation in hot periods plays a more crucial role in temperature decreases than orientation. Furthermore, based on a simulation study in a hot arid climate, indoor thermal comfort was found to have been best improved with a South orientation (Mahar et al., 2019).

The use-case building selected for a one-year experiment is proposed in an office building. Despite this use-case pertaining to an office building, other building typologies in Qatar, such as residential, commercial, or mix-use of a height below 10m are also applicable for implementing the SGR under study. The office building has been selected for the following reasons:

- Accessibility to the building.
- Ease of data acquisition.
- Under operation and in use building.

- Size and height of the building.
- Support offered by the users of the office building.

Moreover, both bare and SGRs are exposed to direct sunlight and wind breeze. It is essential to highlight that both areas selected are in the exact location. Purposefully, to gather data by observation and experimentation, thereby simulating different conditions in a similar climatic setting to compare the outcomes. A comprehensive investigation assessed through a thorough analysis of multiple published studies the mitigation potential of the UHI effect on a city scale (Santamouris, 2014). This was to determine its effectiveness at a particular building height. The study by Santamouris (2014) evidently presented that green roofs heat island mitigation potential effectiveness is higher when the building height is lower than 10m. Hence, the selection of the use-case office building upon the arrival of this conclusion. With this understanding, the SGR was strategically implemented, depicted in Figure 67.

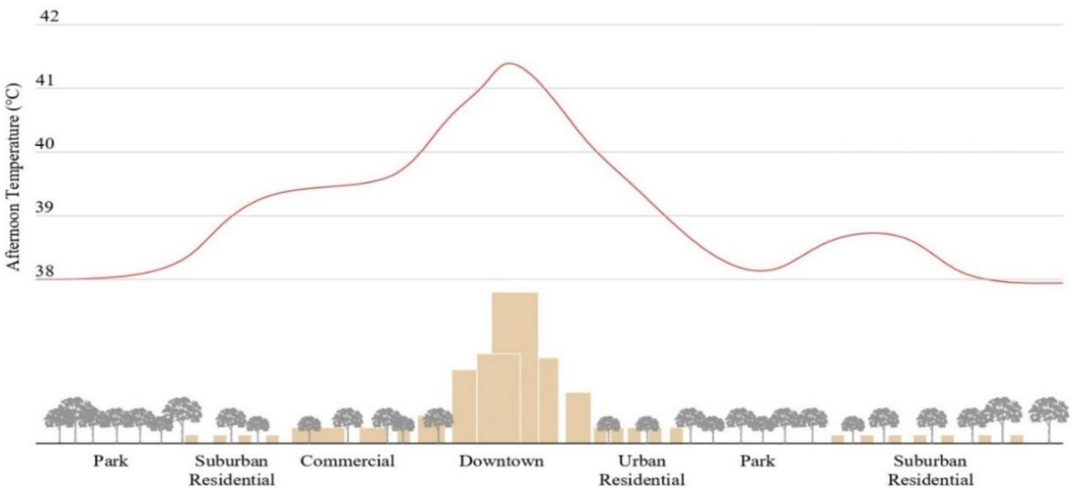


Figure 67. Sketch of a UHI profile of different districts in the Doha metropolitan area.

As mentioned, two areas are selected on an existing roof level (Figure 68), approximately 3.2m^2. The SGR comprises a fixed constant of 20cm soil thickness.

Additionally, comparison and analysis of different local plant types are completed: ground cover, annuals, perennials, succulents, evergreen plants, and native plants.

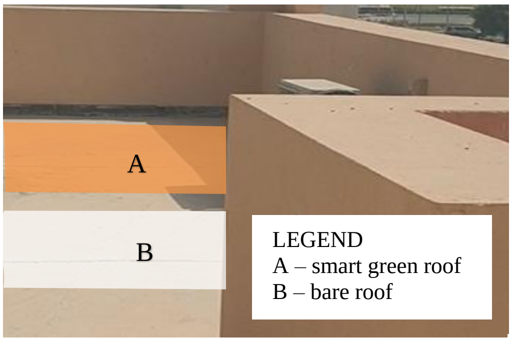


Figure 68. Outdoor location of bare and smart green roofs.

Two identical prototype office rooms have been selected for the study. The location of the indoor experiment lies under points A and B, shown in Figure 68, on the first floor level in Room 10 (Figure 69). The room includes 10A SGR (15.4m^2) and 10B bare roof (15.4m^2), where data loggers are installed for the experimentation phase, as shown in Figure 70. Thus, the SGR comprised a part of the building roof, equivalent to approximately 20% of room 10A inside the office building. Calibration and validation are developed for the simulation based on the 20% of SGR used as a guide based on real-time data.

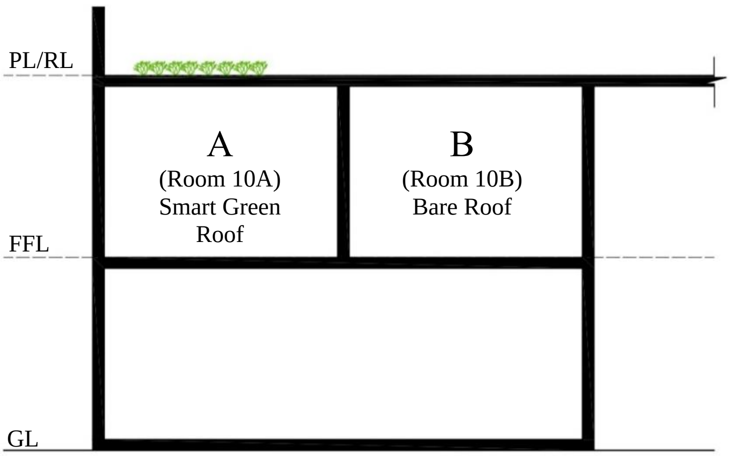


Figure 69. Section A-A showing bare (10B) and smart green (10A) roofs.

Note. GL, ground level; FFL, first floor level; PL, penthouse level; RL, roof level.

Figure 70. Real-time and simulated DesignBuilder location of bare and smart green roofs on the first floor level.

The size of the green roof in the literature varies widely, but the driving factor that determines the green roof size depends on the study's purpose. For example, to design and model an extensive green roof under real climate conditions, a large $5500m^2$ green roof is set up in New York to quantify hydrologic performance over 21 months (Squier-Babcock & Davidson, 2020). Squier-Babcock and Davidson (2020) prove that the large-scale green roof is effective in retaining rainfall and reducing peak runoff, however, soil moisture remains high in winter, and thus its ability to retain volume is diminished. Similarly, Worthen et al. (2021) reach the same conclusion regarding green roof performance in New York through a simulation model. However, they calibrate to larger rain events rather than focusing on the green roof's ability to retain rainfall over a period of time. The purpose behind implementing an extensive small-scale SGR for this dissertation is to study the extent of its impact on environmental changes when installing it on an office building in a hot arid urban setting. A primary reason that only a portion of the roof had an SGR installed is budget limitations. Moreover, green roofs extend from $2000m^2$ to $20m^2$. An example of a small area is urban farming, such as the Green City Growers in London (Green City Growers, 2016).

5.4 Building Envelope of the Use-Case

The building envelope is made up of a roof, walls, floor, windows, and doors working in a cycle to achieve design performance (Figure 71). These components have an impact on heat exchange between outdoor and indoor environments. The thickness of the building envelope components is a primary factor in the amount of heat transfer dissipating into the building (Shao et al., 2021). Table 28 explains the building envelope elements of the use-case, including SGR, bare roof, walls, floors, and windows (office building).

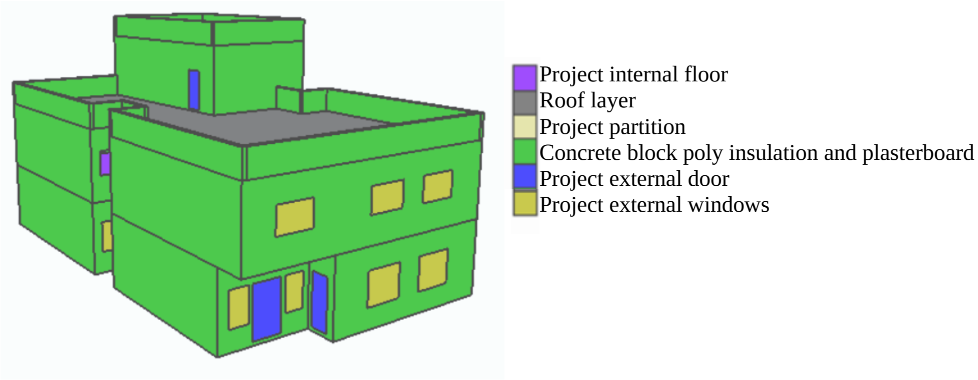
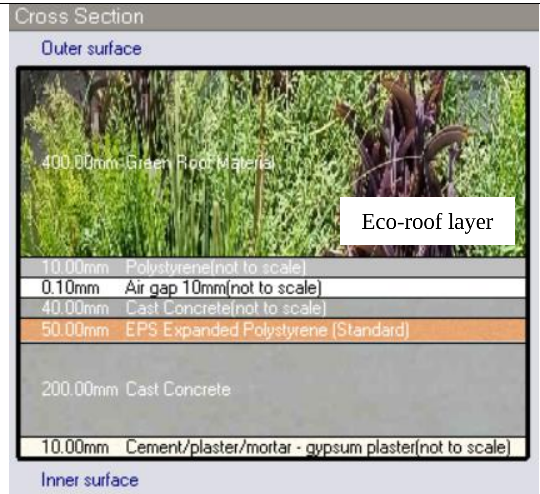
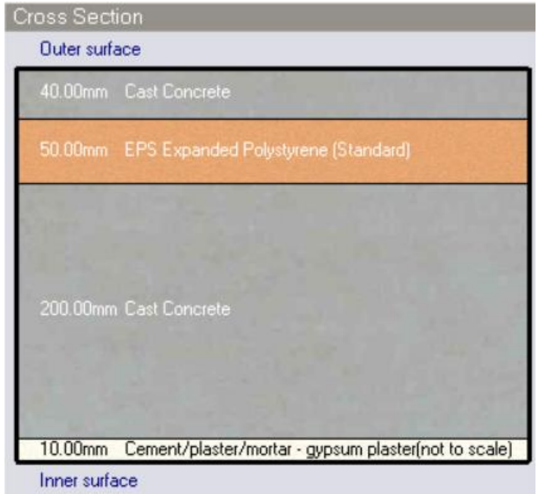
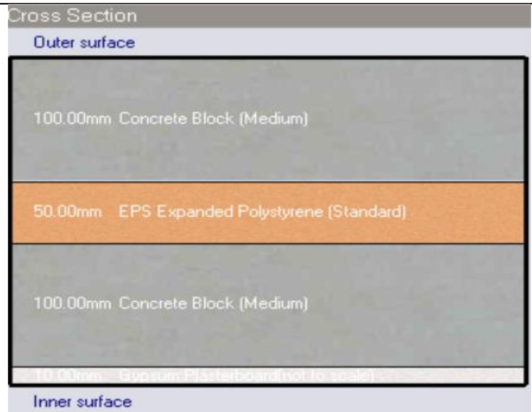


Figure 71. Office building envelope modelled in DesignBuilder.

Table 28. Detailed component of the use-case building envelope elements

Envelope System	Description of System	Total Thickness (m)	System Section	U-Value (W/m^2K)	R-Value (m^2K/W)	k (W/mK)
Smart Green Roof	0.4m green roof material (outermost layer), 0.01m plastic pod system, air gap, 0.04m reinforced cast concrete, 0.05m expanded polystyrene, 0.2m reinforced cast concrete, 0.01m gypsum plasterboard (innermost layer)	0.710		0.440	2.270	0.312
Bare Roof	0.04m reinforced cast concrete (outermost layer), 0.05m expanded polystyrene, 0.2m reinforced cast concrete, 0.01m gypsum plasterboard (innermost layer)	0.300		0.580	1.720	0.174

Envelope System	Description of System	Total Thickness (m)	System Section	U-Value (W/m^2K)	R-Value (m^2K/W)	k (W/mK)
Walls	0.1m concrete block (outermost layer), 0.05m expanded polystyrene, 0.1m concrete block, 0.01m gypsum plasterboard (innermost layer)	0.260		0.460	2.170	0.120
Floors	0.1m reinforced concrete (outermost layer), 0.025m screed, 0.01m carpet (innermost layer)	0.135		1.900	0.530	0.257
Windows	0.004m tinted glass, 0.012m air gap, 0.004m tinted glass	0.020		2.700	0.370	0.054

Note. R-Value, thermal resistance; U-Value, overall heat transfer coefficient; k, thermal conductivity; m, meter; m^2K/W, meters squared kelvin per watt; W/m^2K, watts per square meter, per degree kelvin; W/mK, Watts per meter-Kelvin.

Table 29 emphasizes the green roof material data regarding thermal bulk properties, thermal parameters, and surface properties. Furthermore, Table 30 elaborates on the Building Energy Modelling (BEM) input categories, features, characteristics, and specifications of the office building studied.

Table 29. Smart green roof model materials data, including plant and thermal properties in DesignBuilder software; Eco-roof layer

Smart Green Roof Plant and Thermal Properties	Value	Units
Thermal Bulk Properties		
Conductivity of dry soil	0.5400	W/mK
Specific heat of dry soil	840.00	J/kgK
Density of dry soil	1960.0	kg/m^3
Green Roof Thermal Parameters		
Height of plants	varies - based on real-time data	cm
Leaf area index (LAI)	varies - based on real-time data	no unit
Leaf reflectivity	0.2200	no unit
Leaf emissivity	0.9500	no unit
Minimum stomatal resistance	180.00	s/m
Max volumetric moisture content at saturation of the soil layer	0.4500	%
Min residual volumetric moisture content of the soil layer	0.0100	%
Initial volumetric moisture content of the soil layer	0.1500	%
Surface Properties		
Thermal absorptance (emissivity)	0.9000	no unit
Solar absorptance	0.6000	no unit
Visible absorptance	0.6000	no unit

Table 30. Basic Building Energy Modelling input categories and features of the building studied

Characteristics/ Specification	Description of the Housing	Data Source
Location	Qatar (25.25N latitude, 51.57E longitude, and 10m above sea level)	DesignBuilder
Shape	Rectangular	
Category	Office Building	
Number of levels	3 (ground, first floor, penthouse). Refer to Figure 72	
Floor-to-floor height	3.0m	
Total building height	9m+1.2parapet wall; total of 10.2m	
Location of SGR	First floor at 6m high, and penthouse at 9m high	
Area	Gross: 614.15m^2; ground floor: 272.45m^2; first floor: 279.20m^2; penthouse: 62.50m^2	
Weather file	Doha, Qatar 2021	
Roof	Refer to Table 28 for bare and SGRs	American Society of Heating, Refrigerating and Air-Conditioning Engineers ASHRAE 90.1
Walls	Refer to Table 28	ASHRAE 90.1
Floors	Refer to Table 28	ASHRAE 90.1
Windows	Refer to Table 28	ASHRAE 90.1
Occupancy	0.00019 people/m^2	ASHRAE 90.1
Lighting power density	3.4W/m^2-100lux	ASHRAE 90.1
HVAC system type	Residential system (constant – volume Direct Expansion Cooling Air Conditioning (DX AC))	Commercial Buildings Energy Consumption Survey (CBECS) 2003

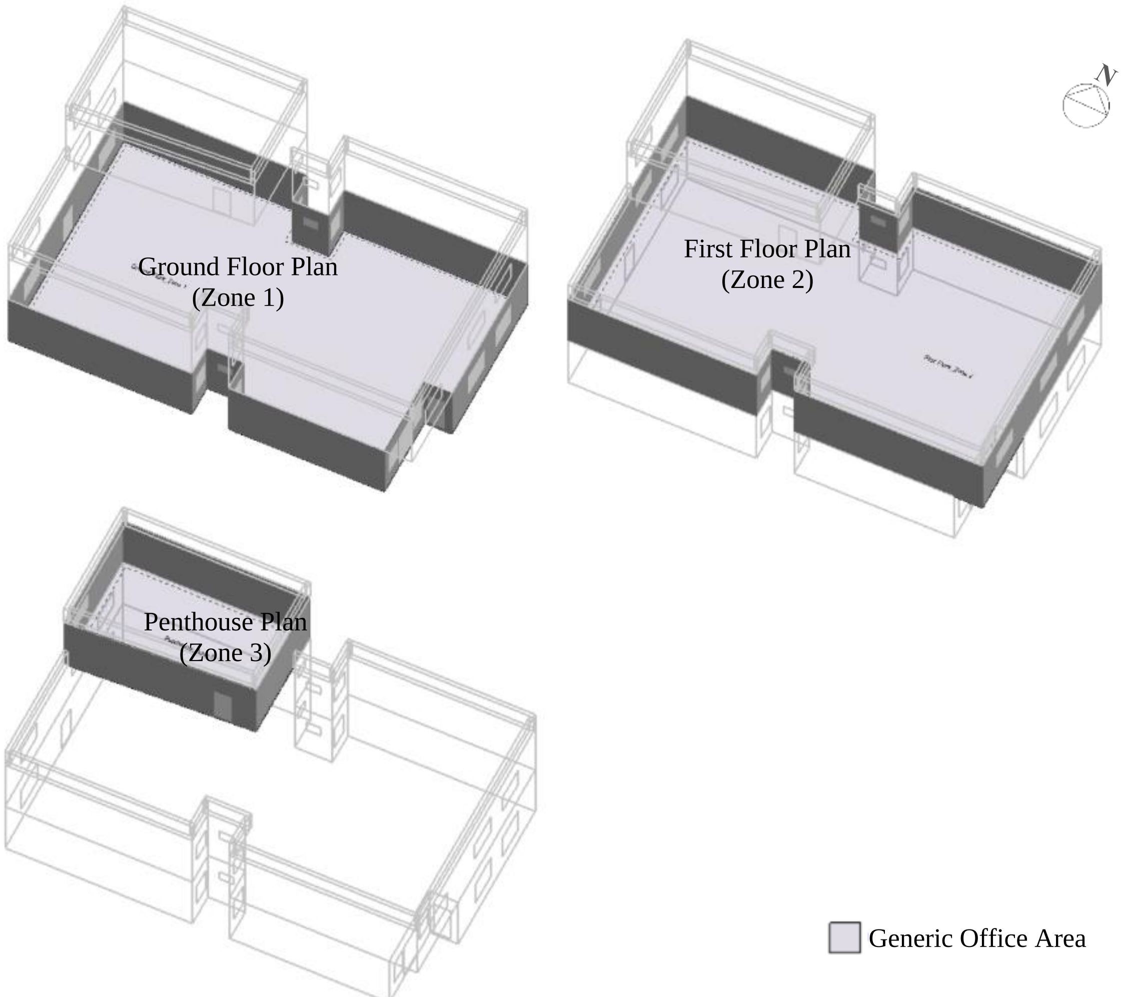


Figure 72. Building floor plans indicating zones, in DesignBuilder simulation software.

Moreover, it is also essential to describe the features and specifications of the building's cooling systems. This includes capacity (tonnage) data, temperature set-points of direct expansion air-conditioning units, and supply air and outside air requirements. During the SGR experiment, it was ensured that the rooms (10A and 10B) used for measuring the indoor thermal properties were continuously air-conditioned with the thermostat set point temperature of 22°C, as the experimental enclosed room was occupied.

Figure 72 presents the building floor plans indicating the three different zones in DesignBuilder; zone 1: ground floor plan, zone 2: first floor plan, and zone 3: penthouse floor plan. Each floor has one HVAC unit. In each zone, the air definition is based on outside air and supply air requirements. Each zone was analyzed by comparing its SGR state to its bare roof state. Comparing bare and SGRs for each zone was crucial to understanding energy consumption in the building better.

5.5 Qatar Smart Green Roof Application the Use-Case

This section emphasizes the type of SGR, structure, plants, and smart irrigation system to be used in the experimental real-time approach, as listed in Table 31.

Table 31. Selected smart green roof features for the real-time experimentation phase

Green Roof	Description
Type	Extensive - lightweight
Structure	Modular pod system (plastic pod, drainage, vigoroot geotextile wicking material, growing medium, and plant)
Irrigation system	Phase 1: manual irrigation Phase 2: smart, sustainable drip irrigation IoT automation platform (IRRIOT)

5.5.1 Type and Structure of Smart Green Roofs

Existing building structures are used for the research having an extensive modular lightweight roof system, offering minimal cost and low maintenance. The SGR is based on a modular pod system, vigoroot geotextile wicking material, growing medium at 20cm, and stress-tolerant and low-, self-growing plants, as discussed in this section and detailed in Figure 73.

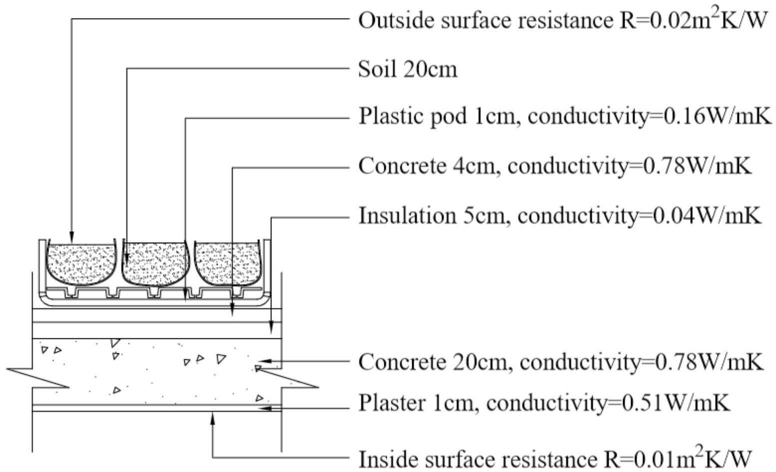


Figure 73. Smart green roof detail illustrated as a CAD drawing.

The use of multiple layers and different membranes achieves SGRs' purpose in reducing heat gain. Thus, it is crucial to examine the roof's existing and experimental design components. The thickness, R-Value, U-Value, and thermal conductivity (k) of each roofing material must also be specified (Table 32).

Table 32. Smart green roof layer detail using DesignBuilder

Roof Detail	Thickness (m)	R-Value (m^2K/W)	U-Value (W/m^2K)	k (W/mK)
Gypsum plaster	1cm/100 = 0.01m	0.16	6.27	0.51
Concrete	20cm/100 = 0.20m	0.40	2.52	0.78
Expanded polystyrene (insulation)	5cm/100 = 0.05m	1.39	0.72	0.04
Concrete	4cm/100 = 0.04m	0.19	5.23	0.78
Plastic pod	1cm/100 = 0.01m	0.20	4.94	0.16
Clay soil	20cm/100 = 0.20m			
- **Dry**		2.75	0.36	0.07
- **40% moisture content**		2.08	0.48	0.01

Note. R-Value, thermal resistance; U-Value, overall heat transfer coefficient; k, thermal conductivity; m, meter; m^2K/W, meters squared kelvin per watt; W/m^2K, watts per square meter, per degree kelvin; W/mK, Watts per meter-Kelvin.

A total of 16 pods are used for the study, exemplified in Figure 74. Each pod consists of 3 plants, equating to 48 plants in the SGR.

Figure 74. Green leaf brand, plastic pod system.

The vigoroot geotextile wicking fabric is able to hold 5L, shown in Figure 75. The fabric works by air-pruning the roots of plants (Figure 76). However, the roots need oxygen, and the vigoroot fabric is able to adapt the root formation, thus enhancing plant sustenance in limited soil substrate volume. This change encourages more vigorous rooting, enabling the plants to absorb more nutrients. Helping prevent the plants from becoming pod bound, the vigoroot wicking fabric restricts long root growth. This altered root growth state allows plants to resist harsh weather, pests, and diseases.

Figure 75. Vigroot geotextile wicking fabric (Source: Greenwood, 2019).

The main root grows straight down the grooved cell towards the large drainage opening at the bottom

The tips make contact with the air and die off

The plant then compensates by producing new root growth with no root balls

Figure 76. The growing process of an air pruning pod (Source: Greenwood, 2019).

Moreover, vigoroot fabric is porous and drains well, helping prevent roots from getting saturated, but the planter may dry out quickly. Furthermore, the planter requires more water because it grows larger than usual. As such, frequent watering is needed, and by touching the top of the compost and the fabric at the planter's base, the moisture content in these places should indicate watering needs.

Ordinary multi-purpose compost is recommended for most plants. The type of compost influences the water needs of the planter. Plants are planted in a lightweight and fertilized 20cm growing medium supplied by the local Ministry of Municipality and Environment (MME). The growing medium combines 70% sweet soil, 15% peat moss, 10% coco peat, and 5% bi-solid organic.

Qatar’s high temperatures and long droughts can negatively impact plantations. In turn, the diversity of the plants that could be used becomes very limited and more expensive to maintain. Native plants suitable for Qatar's climatic and ecological conditions have been selected to conduct this research. The plants chosen for the study are local hardy species inclusive of Aptenia (Haialam), Sesuvium portulacastrum, Asparagus Ferns, Tradescantia Pallida, Aloe Vera, Agave Americana, Euphorbia MillBig, Pennisetum Setaceum, Eremophila Maculata, and Ruellia Brittoniana, illustrated in Figure 77. These succulent and ground cover plants are selected to:

- Control extreme temperature and humidity levels entering the building structure
- Protect the building from winds, solar radiation, and extended droughts
- Survive in Qatar's hot arid climate with minimal water and fewer nutrients
- Apply minimal load on the building's structure
- Resist multiple sources of stress-related living conditions of the roof structure
- Require little maintenance, enhance the aesthetic, and improve environmental conditions

Figure 77. Plants used in the real-time experimentation phase.

There is an apparent lack of published journal articles and literature regarding the particular arrangement of plants that form a green roof. For this research study, the arrangement of the plants in Figure 77 has been made based on two premises. First and foremost, they have been carefully arranged to achieve a united system requiring equal and compatible water needs, noting that most of the selected plants require very little water. Secondly, arrangement, to some extent, has a degree of variability and randomness due to the researcher's bias as per the aesthetic component.

5.5.2 Irrigation System for Smart Green Roofs

The irrigation system included two phases: phase 1 being the manual irrigation from 1 March 2021 to 30 April 2021, and phase 2 being the smart, sustainable drip irrigation system starting from 1 May 2021 to 28 February 2022, illustrated in Table 33. The phase 2 smart irrigation system is detailed in Figure 78, showing a section of the SGR, installed drip line, and drainage system.

Table 33. Types of irrigation in the research experiment

Date	**Phase**	**Irrigation type**
01-03-2021 to 30-04-2021	Phase 1	Manual irrigation
01-05-2021 to 28-02-2022	Phase 2	Smart, sustainable drip irrigation IoT automation platform (IRRIOT)

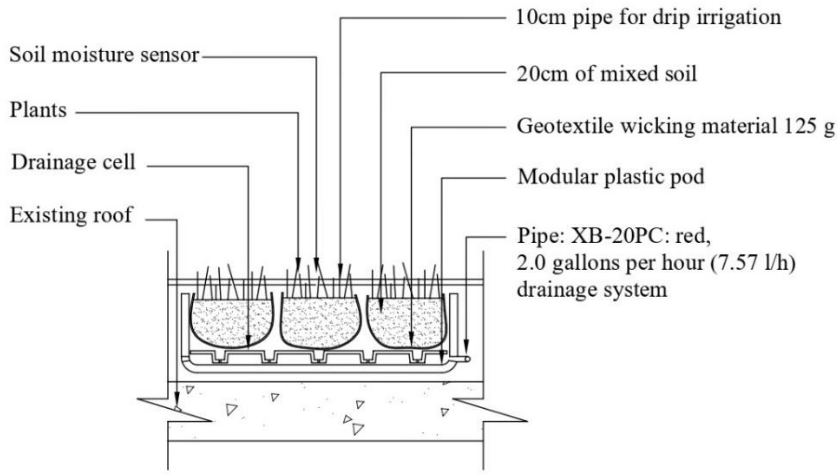


Figure 78. Detail of smart green roof and irrigation system.

For this research, drip irrigation is the chosen method of watering the extensive SGR. A drip irrigation system is controlled over an automated system using sensors and activators (including soil moisture sensors) to irrigate the plants. The smart IoT automated system, IRRIOT, is cloud computer-based and provides the means for remote access, control, and storage of smart precision irrigation. The smart irrigation system is an advanced technology that uses sensors to inform watering patterns and modify the irrigation schedule to improve efficiency. Through real-time data on soil moisture from the sensors, the smart irrigation system aims to reach optimal soil conditions by intelligently supplying the required water to the intended area. Figure 79 explains the process of programming the smart irrigation system to start or stop irrigation.

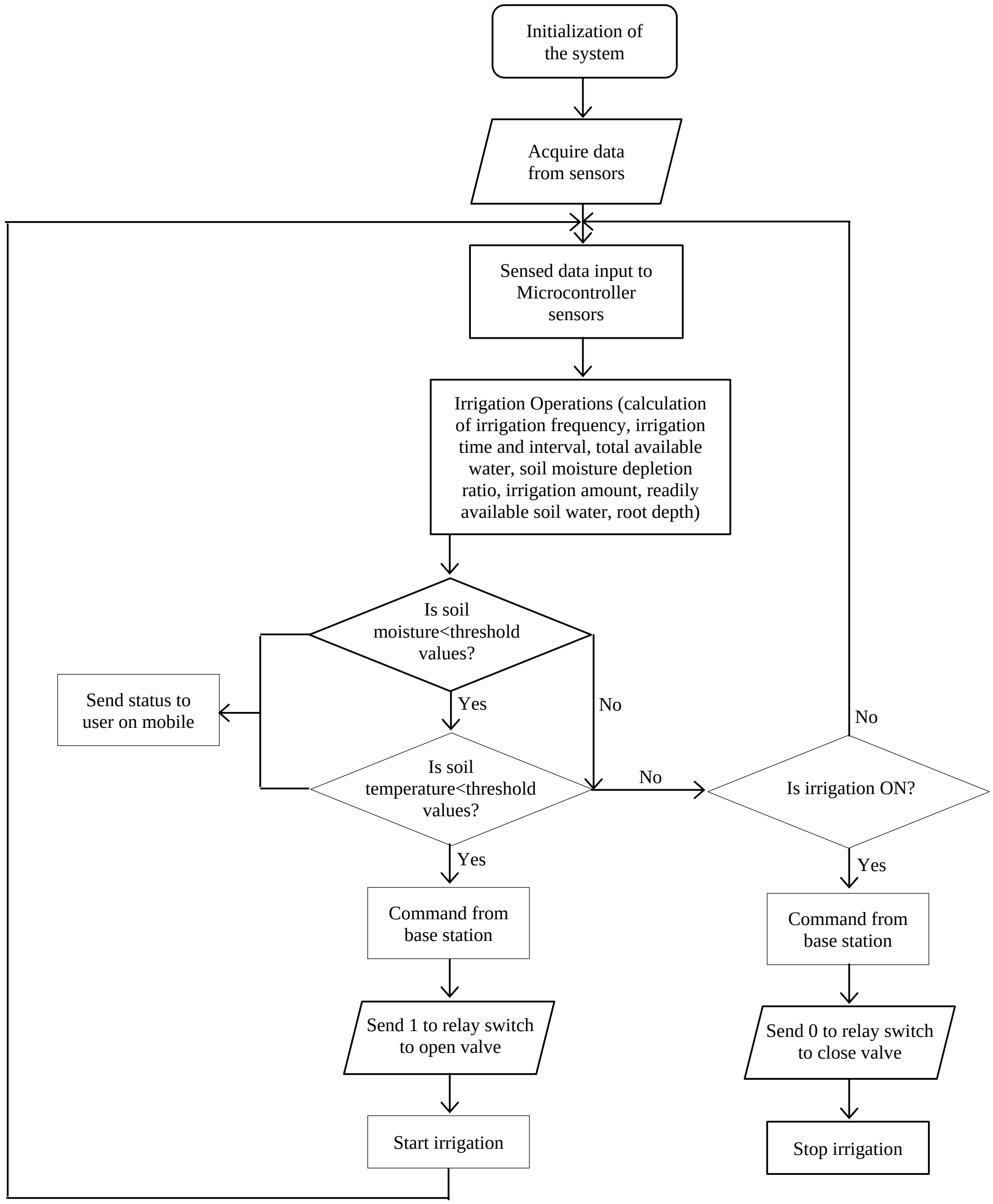


Figure 79. Smart green roof irrigation decision-making conclusion is illustrated in a schematic diagram of the prediction algorithm.

The smart irrigation system (SIS) is composed of 4 experiments to assess and achieve the optimal level of water consumption based on the soil moisture of the plants, which is affected by climatic conditions on the roof level over the year. This is enforced by the graphic displayed in Figure 80. During experiment 1, the automation condition was not applied, but the controller was set to water the plants at 7 pm after sunset for half an hour every second day. Experiments 2, 3, and 4 were based on applying the upper threshold automation condition. Experiment 2 was set to stop irrigation at a soil condition trigger of over 60%, experiment 3 at over 45%, and experiment 4 at over 40%, implying that the smart irrigation sensor would cut as per the configuration level. Essentially the watering was cut off when the soil moisture was above the set trigger. As a resolution to ensure plants receive the required water per day, the irrigation system was programmed at time intervals. The soil moisture sensor sustained the program of the smart irrigation system, with experiment 2 set to water plants six times a day for a duration of 30 minutes each (Figure 81), while experiments 3 and 4 were to water the plants three times a day for the same duration each time, as presented in Table 34.

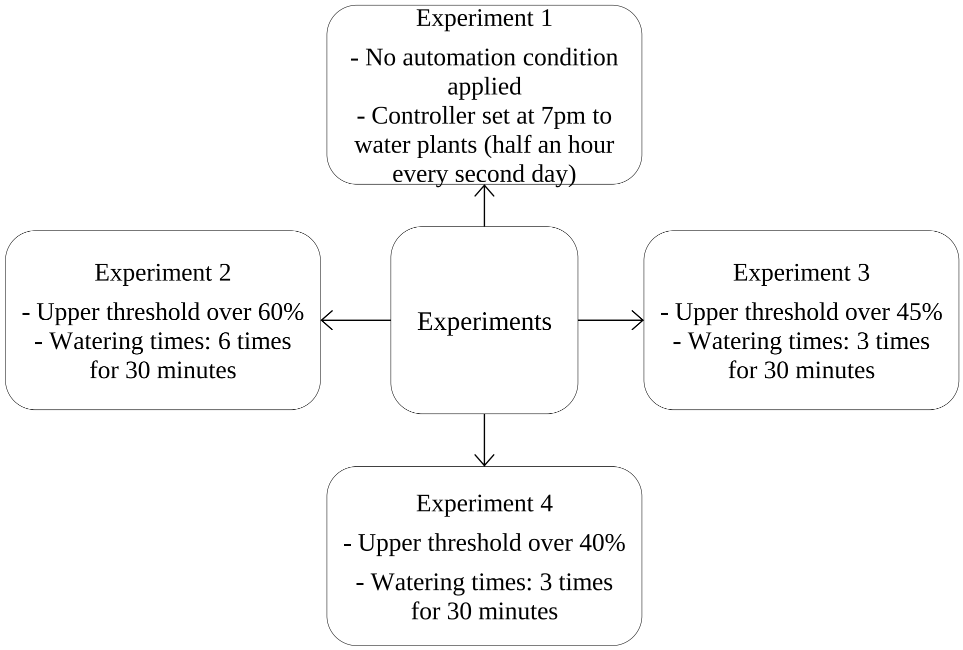


Figure 80. Experiments as part of the SIS based on soil moisture sensors.

Table 34. Irrigation system of SGR with the application of a soil moisture sensor

Date	System	Soil Moisture Sensor			Watering Times
		Mode	Trigger (upper threshold)	Reset (lower threshold)	
Mar-21 **Apr-21**	**Manual**		N/A		Every day at 7 pm (amount is dependent on needed watering volume as per observation).
May-21	**Smart - Experiment 1**		N/A		7 pm after sunset for half an hour every second day.
Jun-21	**Smart - Experiment 2**	Active	Over 60%	None	Six times a day for 30 minutes each at 7:00 am, 10:00 am, 12:00 pm, 2:00 pm, 4:00 pm, and 7:00 pm.
Jul-21 **Aug-21** **Sep-21** **Oct-21**	**Smart - Experiment 3**	Active	Over 45%	None	Three times a day for 30 minutes each at 7:00 am, 12:00 pm, and 4:00 pm.
Nov-21 **Dec-21** **Jan-22** **Feb-22**	**Smart - Experiment 4**	Active	Over 40%	None	Three times a day for 30 minutes each at 7:00 am, 12:00 pm, and 4:00 pm.

Figure 81. Configuration of automation condition for SIS, experiment 2.

For the project's purpose, a drip line, Netafim Uniram RC 16x1,0/1,6 20, with 20cm intervals, is selected. The outlets were placed every 20cm on each plant to allow watering. The drip line is parameterized, providing 7.57 liters per hour of water. The structure of the smart irrigation system is demonstrated in Figure 82, downstream from the valve. Moreover, to install the smart irrigation system securely, the drip line was connected via pin placement to the soil, as shown in Figure 83.

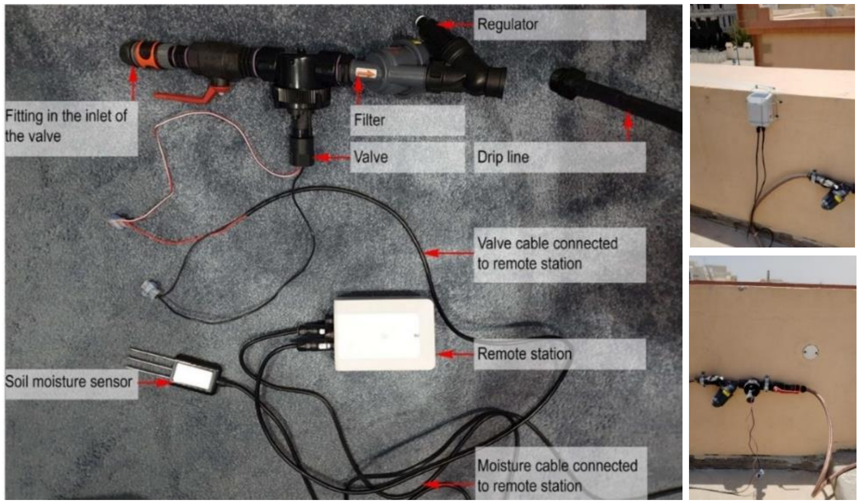


Figure 82. Smart irrigation system structure.

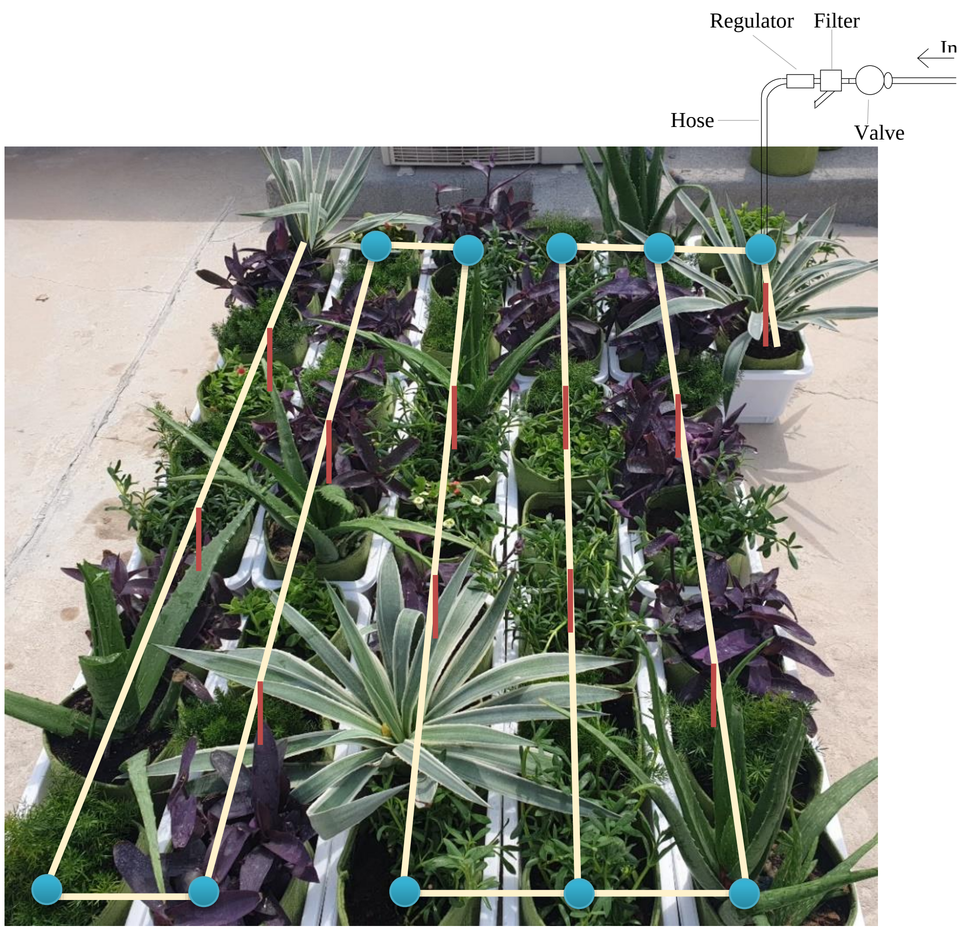


Figure 83. Installation of irrigation system layout: drip line, connectors, and pins.

Note. Beige color, drip line; blue color, right angle connectors; orange color, pins.

5.6 Conclusion

The current chapter aimed to outline a comprehensive outlook of the design of the experimental research study. Through a thorough recent literature review evaluation, the use-case variables were explored and justified. In summary, due to the meteorological and climate circumstances of the study area, Qatar, several factors of the bare roof and SGR components must be considered. The type and structure of the extensive SGR have been exhausted, with a close look into the smart irrigation system of choice for experimental research. An extensive lightweight modular pod system connected to a smart irrigation supply studies the relationship between SGR implementation and environmental improvements in energy consumption and user thermal comfort. Determining a valid link between SGR application and the combination of reduced heat gain and improved environmental quality, this study design allows for a better understanding of confounding variables and whether there is a causation between roof types and environmental quality in low-rise buildings, with considerations of the influence on user thermal comfort.

A thorough comprehension of Qatar's meteorological data, study area, selection criteria, and building envelope allows for assessing the research factors under study. Thereby, plant performance parameters and environmental factors are evaluated thoughtfully, resulting in a cohesive interpretation of results. Furthermore, knowing that water resources are rare, with rainfall primarily occurring in only six months of the year, allows for customizing a smart application for the experimental green roof.

The section on the SGR application use-case in hot arid Qatar goes on to document experimental protocols and research procedures. This further ensures reliability and reinforces findings in the face of repeatability measures and data reproducibility. This chapter gives an overview of the use-case experiment, thus allowing the evaluation and analysis of the data acquired, as presented in the following chapter.

CHAPTER 6: DATA ACQUISITION AND ANALYSIS

6.1 Introduction

The following chapter consists of qualitative and quantitative data acquisition and analysis related to bare and smart green roofs (SGRs). The former deals with data obtained through conducting an interview targeted at retrieving experts' considerations for SGR implementation in Qatar. As for the latter, the questionnaire aimed at collecting and analyzing users' responses. Quantification of the data collection of plant arrangement and color was conducted. Quantitative real-time data is measured for thermal temperature, plant growth, smart irrigation and drainage systems, wind speed, temperature, humidity, and heat flux. Quantitative data acquisition and analysis also encompasses DesignBuilder simulated data, similarly presenting wind speed, temperature, humidity, heat flux, and energy consumption figures. Along with data obtained on thermal conductivity, U-Value, and R-Value, with a particular focus on the single day that experienced peak temperature and heat flux simultaneously, and a look into the energy demand from sensible cooling. This serves the analytical and interpretative purpose, discussed in the following chapter, of assessing the association between users' thermal comfort and building energy consumption.

Analysis of environmental factors through means and standard deviations is used to assist the interpretation of findings, which is discussed in the next chapter. Statistical analysis is employed to extract the *p* value among the plant performance parameters against the environmental factors to determine how probable the research findings are, not caused by chance. These results will help associate significance with the factors important to SGR influences. The lower the *p* value, the stronger the evidence of the statistical importance of the observed difference. A *p* value of less than 0.05 is statistically significant, as there is less than a 5% probability that the results are random.

6.2 Qualitative Data Acquisition and Analysis

This section provides qualitative data acquisition and analysis. It is composed of data obtained through one-on-one sessions. The interview collected responses from experts in the fields of green roofs, sustainability, urban planning, and architecture. This interview involved 15 participants belonging to a range of professions from academia and industry. The interview was designed to assess the knowledge and awareness level of SGRs. It captures technical feedback, perceptions, understanding, and barriers towards designing, developing, and implementing an appropriate SGR system that fits within the context of Qatar's hot arid region for both new and existing buildings.

Most experts were familiar with green roofs due to research completed or work involved in Egypt, Dubai, and other western countries such as America and Switzerland. They discussed the lack of successful and ongoing implementation of SGRs around the Gulf region. The few more heavily involved with SGRs also shared the same viewpoint. A landscape architect previously working in Dubai mentioned his familiarity with semi-intensive and intensive green roofs and his previous involvement with Dubai's Meydan Racecourses and green roofs. A higher number of experts were, in fact, more familiar with semi-intensive and intensive green roofs than extensive green roofs. As shown in Figure 84, the experts know the types of green roofs, including extensive, semi-intensive, and intensive.

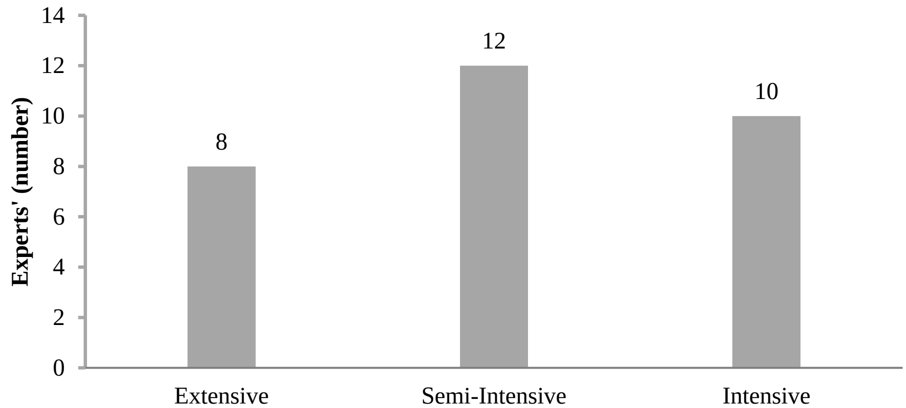


Figure 84. Fifteen experts' familiarity with type of green roof design.

Figure 85 illustrates the opinion of field experts' as to the purpose of green roof implementation on the building. The majority of the targeted interview respondents strongly agree that green roofs reduce ambient air temperature, improve outdoor air quality, and reduce the energy consumption of buildings. A few experts decided that while the energy consumption of buildings is reduced, a large amount of green roof application and surface area is needed to achieve such a result. The relative air temperature was greatly identified and mentioned, with reference to regions of Qatar, such as the Corniche area, that have a 5°C lower temperature than outside due to more bulky plant species, such as trees and grass. Other experts greatly aided the use of green roofs for the improvement of air quality and reduction of CO_2 in the atmosphere, as Qatar has one of the highest CO_2 emissions, as well as the improvement of indoor air quality, user comfort, and increase of wildlife and biodiversity. None of the interviewed experts strongly disagreed with any of the benefits green roofs can provide; however, several disagreed with their ability to improve public health, reduce noise, and reduce the ambient temperature.

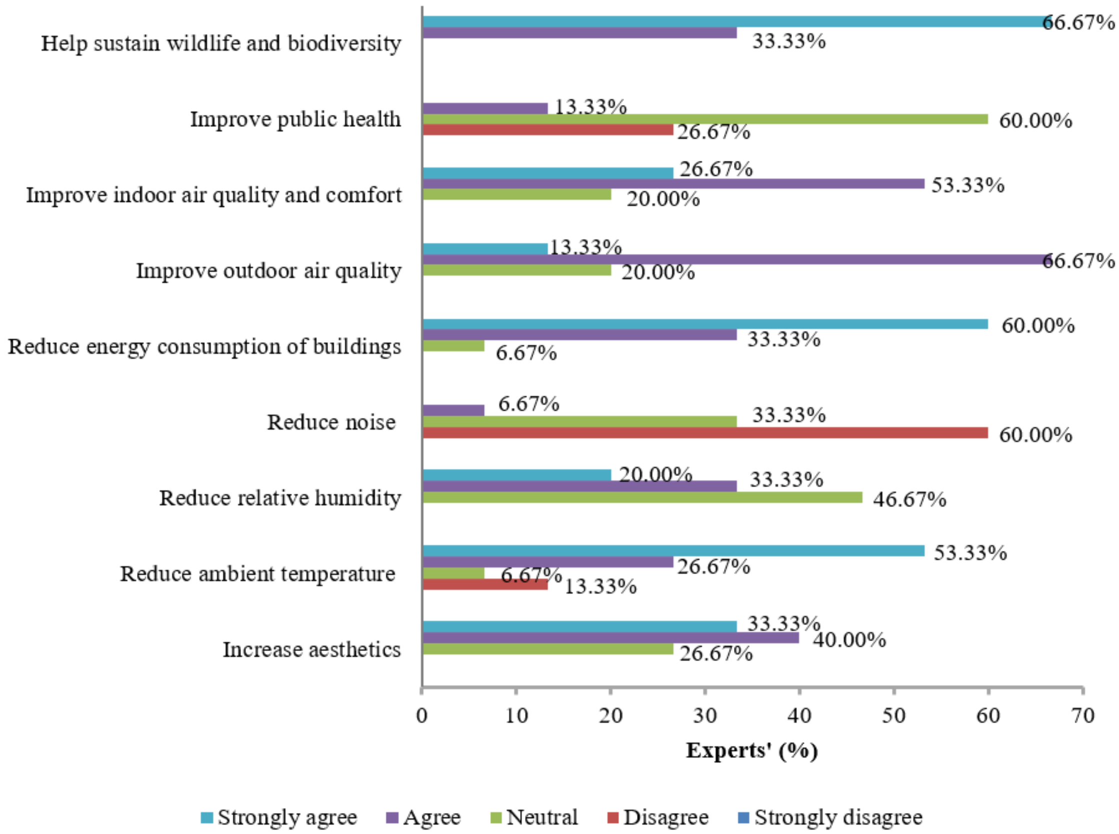


Figure 85. Fifteen experts' opinions on the purpose of green roofs on the building.

As shown in Figure 86, all experts had common viewpoints on the difficulties faced by implementing SGRs. Experts collectively agreed that surface area could be extremely limited at rooftops due to buildings' design and legislative language. A few experts also mentioned the irrigation system in Qatar, as well as water wastage. Other collective agreements from experts included regular maintenance and its cost, structural constraints due to load, and construction difficulties. 80% considered climatic reasons a difficulty faced, while some found no hurdle in locating a variety of appropriate plants that can sustain living in hot and arid climates. 66.67% agreed that for such implementations to be made, local authorities need to act and lawfully implement a building code clause that requires a percentage of greenery. Lastly, 60% found lack of skilled manpower a hurdle, and 40% considered cultural reasons such as privacy and ground-ness (ground closer to nature).

The idea that users cannot visually see the long-term and short-term benefits SGRs can provide as a sustainable lifestyle and environment was highlighted. A shift in perspective was recommended and elaborated upon with reference to Qatar's blockade in 2017. During this time, an expert noticed increased attention and use of growing vegetables in people's front yards through the use of both dry planting and water planting. Due to such a significant change, the people adopted new relationships with plants and produce. The expert underlined this new way of thought as having the potential to be introduced in the front yard and the rooftop. Overall, experts saw no standard or revision regulation applicable for implementing SGRs that suit Qatar's hot arid climate through design and legislative matters.

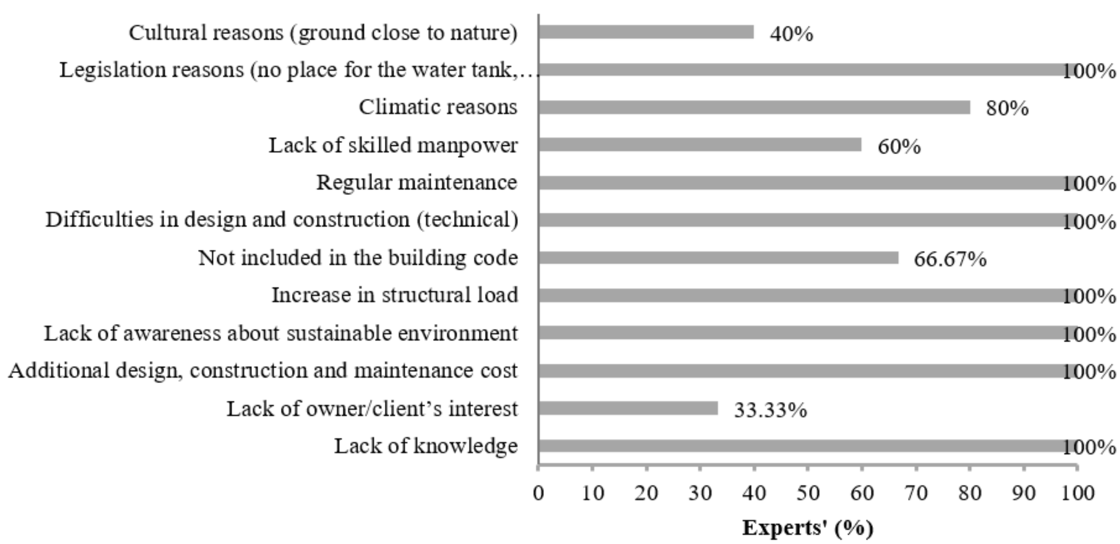


Figure 86. Fifteen experts' opinions on the difficulties in implementing smart green roofs.

All respondents viewed that the measures that can enhance the implementation of SGR systems for new and existing buildings include adopting legislative and governmental decisions such as providing new building codes for contractors/developers and incentives from the government and owners/developers. Most measures included government and higher ministry action to be implemented on all building developments. Most agreed that such measures allow for instant and widespread application. In addition to governmental and ministry codes, an awareness of the importance of sustainable environments needs to be raised to further provide initiative to development investors/owners. While most experts found these measures plausible, a select few found negligence between the government's goals and actions. An observation mentioned that although the government acknowledged increased greenery as needed measures, experts found continuity and implementation of SGRs were at pause due to unseen immediate profits and acceptance. Other measures include introducing SGRs in educational curricula, giving developers bonuses through reducing government fees, and enforcing that a certain percentage of green space be implemented in projects. Lastly, it is important to mention that two experts were skeptical about implementing SGRs on existing buildings as the cost, time, and effort inputted to study the existing structure, load, and surrounding area can sometimes outweigh the benefits of SGRs. This might also be due to the minimal roof space available for SGRs (Figure 87).

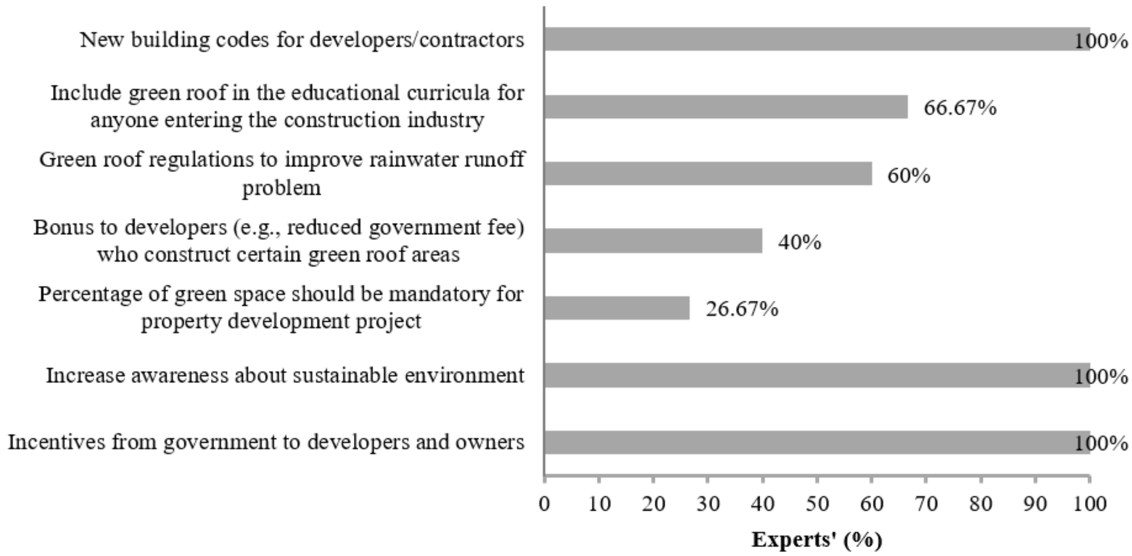


Figure 87. Fifteen experts' opinions on the measures that can improve the introduction of smart green roofs for new and existing buildings.

After the present qualitative data acquisition of experts' opinions, it is analyzed that using an SGR is a potential solution to reduce building energy consumption. This is in conjunction with considering its influence on users' thermal comfort. The remainder of this thesis's data acquisition and analysis represents an in-depth quantitative investigation of the parameters integral to SGR application in existing buildings in Qatar.

6.3 Quantitative Data Acquisition and Analysis

This section presents a questionnaire administered to users from three office buildings. It further demonstrates real-time data, inclusive of quantified visual observations of plants' performance, as well as data on temperature, humidity, wind speed, and heat flux, and simulated data on temperature, wind speed, humidity, heat flux, thermal conductivity, thermal resistance (R-Value), overall heat transfer coefficient (U-Value), and energy demand. Visual data acquisition and analysis of SGR performance parameters, including general plant conditions, plant color, growth, and type, with observations of material maintenance, smart irrigation system type, pipework, and drainage system layout recorded. As per these observations and to ensure SGR system functionality, necessary changes among these parameters have been made to complete the real-time experiment. Quantifying these visual parameters to better understand their role in plant performance, along with generating data through simulation, elicits a more comprehensive interpretation of the building's thermal and energy performance.

The current study implemented simulation analyses of different climatic variables to assess the relationship between simulated environmental indicators against real-time experimental plant performance characteristics. The use of the statistical significance tool, *p* value, gave a measure of the degree of data compatibility, thus, assisting in carrying out graphical representations between environmental factors and plant performance determinants. Selected relationships were evaluated to determine each of the evaluated traits. Simulated indoor surface ceiling temperature, heat flux, and outdoor humidity were examined against leaf area index (LAI) and plant height. For an accurate comparison between simulated and real-time plant performance parameters, the values obtained for parametric input into the DesignBuider simulation software were that of the real-time experimental monthly collected data. Conjointly, assessing simulated data against real-time experimental data is employed to calibrate the simulation tool, DesignBuilder.

6.3.1 Questionnaires

Data was collected and analyzed through a questionnaire to understand and record the indoor environment quality and thermal comfort of 170 office users'. Within the surveyed users' only 88 of the respondents continued with the additional open-ended follow-up questions mainly focused on user comfort level. The users were encouraged to provide their opinion and describe any comfort-related situation that impacted their lifestyle and workplace. The questionnaire comprised four main sections:

- First section: relating to background information;
- Second section: general room perception, user comfort;
- Third section: adaptive strategies (behavioral insights, clothing, and metabolic rate);
- Fourth section: smart green roof awareness level.

The first section of the questionnaire covered the background information of the respondent. The questionnaire was completed by 170 users from the three selected office buildings. Regarding occupation types practiced in the building, 82% of the users surveyed were office workers, 9% were maintenance engineers, and 9% were project coordinators and quality assurance and quality control (QAQC) engineers.

The second section of the questionnaire included the users' general room perception and comfort conditions, consisting of predicted mean vote (PMV) values. Of the 170 surveyed users, 65% worked on the first level and 35% on the ground level of the office building (Figure 88). The PMV during the winter was recorded at 0 for 5% of the users' (feeling neutral), -1 for 93% of the users' (feeling slightly cool), and -2 for 2% of the users' (feeling cool) (Figure 89). Thus, the heating was turned on for 1-2 hours to achieve a comfortable indoor temperature. In summer, the PMV was valued at +3 for 98% of the users' (feeling hot) and +2 for 2% of the users' (feeling warm) (Figure 90). This hot and warm sensation necessitated the air conditioning system to be operational throughout the day.

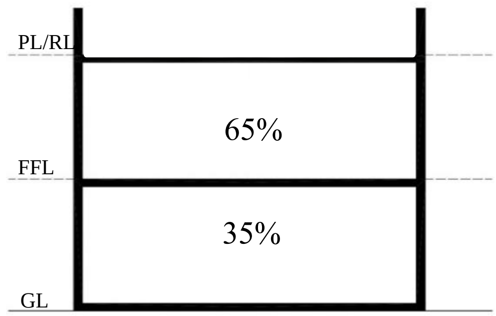


Figure 88. Number of workers that occupied the office buildings on the ground and first floors during the questionnaire.

Note. GL, ground level; FFL, first floor level; PL, penthouse level; RL, roof level.

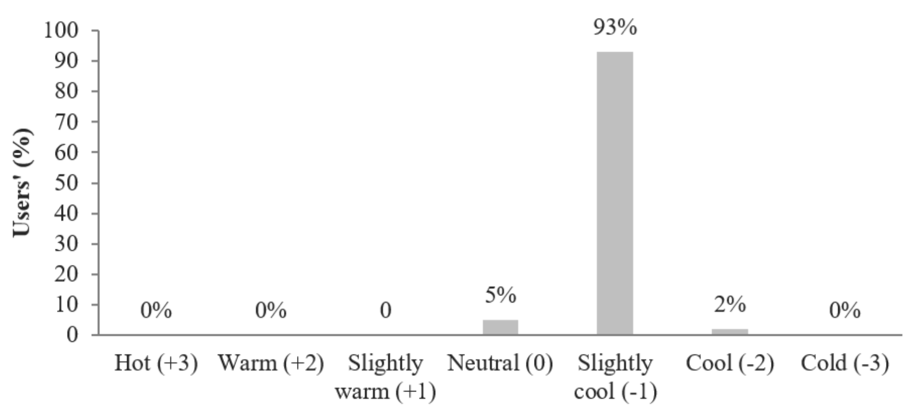


Figure 89. Users' indoor sensation of thermal comfort during winter.

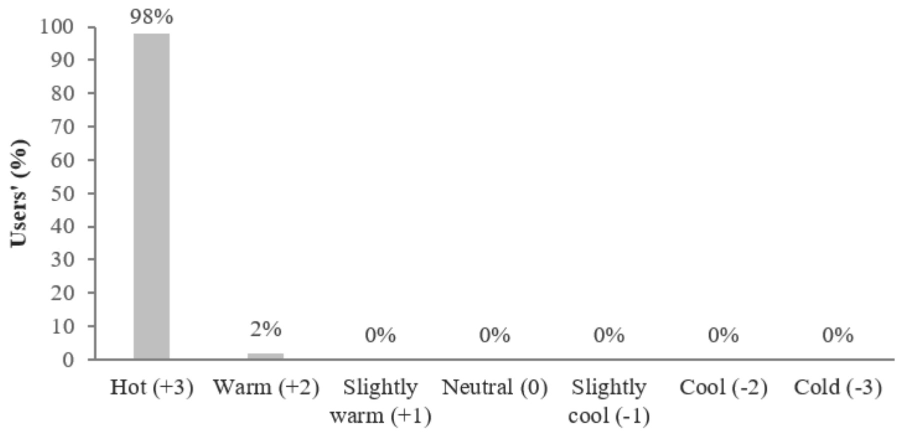


Figure 90. Users' indoor sensation of thermal comfort during summer.

In terms of comfort level, most users responded with improvements in the building temperature, air conditioning, access to daylight, and access to good views, as presented in Figure 91. With respect to these factors, 72.7% responded based on their feeling or perception that there is a decrease in indoor environment quality (IEQ) affected by weather conditions (Figure 92). From these 123 respondents, the summer season was very likely associated, by 80 users, with this decrease in IEQ, while the winter season was ranked neutral by 56 users, as shown in Figure 93. Of the 170 users', 45.5% agree that indoor environment quality problems seem to be most notable in the afternoon, with an equivalent of 45.5% recording that it occurs throughout the entire day (Figure 94). All users indicated that they use air conditioning to combat the indoor environment quality problem mainly related to air temperature. Of these, 90.9% use it most of the day, and 9.1% use it during the morning, illustrated in Figure 95.

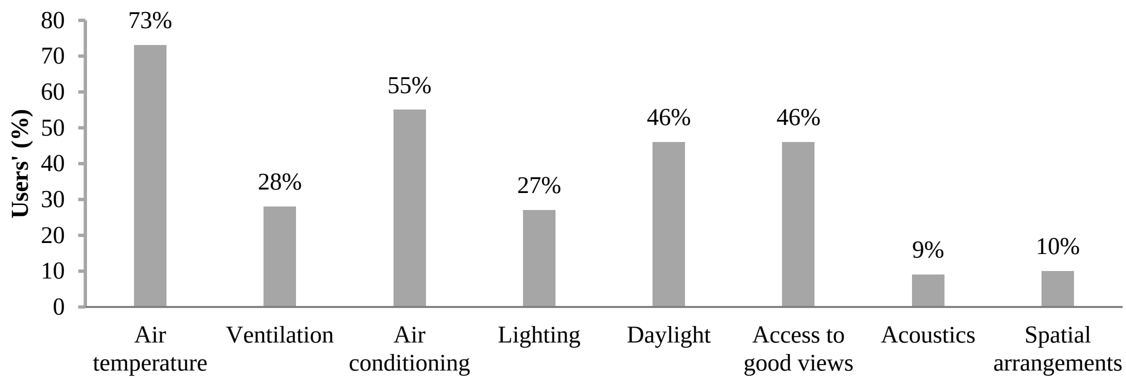


Figure 91. Factors that users want to improve and change.

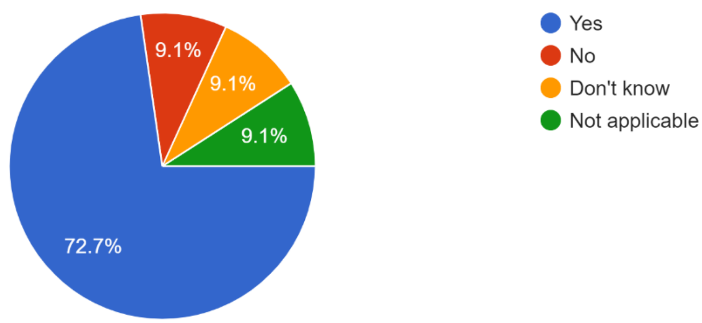


Figure 92. Users' response associating a season to a decrease in indoor environment quality.

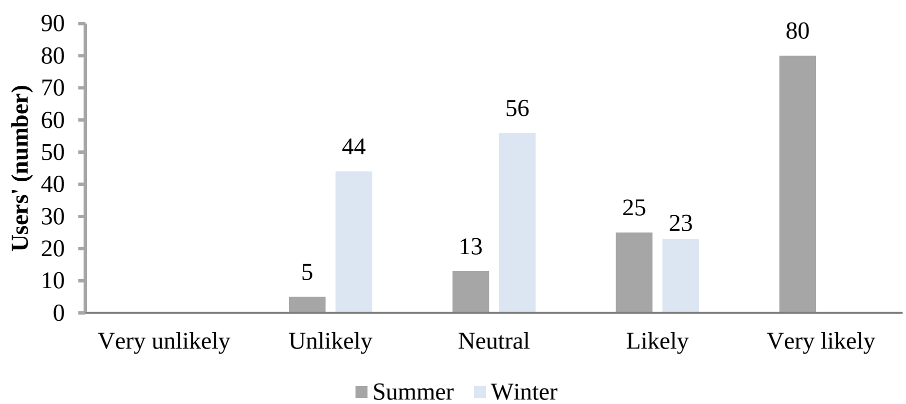


Figure 93. 123 out of 170 users' perception towards a decrease in indoor environment quality.

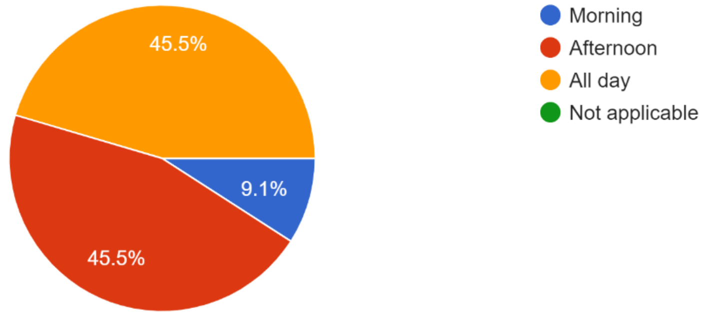


Figure 94. Users' perceptions of when indoor environment quality problems are notable.

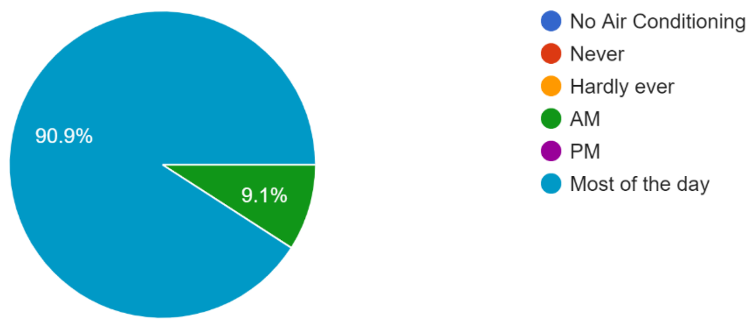


Figure 95. Users' usage of air conditioning.

The third section of the questionnaire involved inquiring about users' strategies to adapt to their thermal environment. Based on open-ended questions, responses were determined to minimize physical discomfort and improve thermal comfort. Users' were either relaxed or seated with minimal activity. Therefore, according to ANSI/ASHRAE Standard 55-2010, the user's metabolic rate is seated with a reading of 1.0.

Another factor surveyed was clothing, an integral thermal comfort study parameter. In Qatar, cultural and social aspects influence clothing choices, directly impacting weather and personal activity level. Responses from a set of questions regarding worn clothing determined the average clothing insulation (clo) values (Rijal et al., 2019) per ANSI/ASHRAE Standard 55-2010 and Figure 44. In winter, both men and women wore long-sleeved shirts with trousers and occasionally jackets, having an average clothing insulation of 0.7 clo. In summer, on the other hand, men sometimes wore t-shirts and long pants, a clo of 0.4. In contrast, women wore shirts or t-shirts, long pants or skirts, with a clo of 0.45. The clo values also take into account undergarments and footwear.

The fourth section of the questionnaire is about the users' familiarity with green roof systems. As depicted in Figure 96, 62% of the 170 respondents were slightly familiar with green roof strategies for mitigating heat. This lack of knowledge is a deterrent to implementing SGRs.

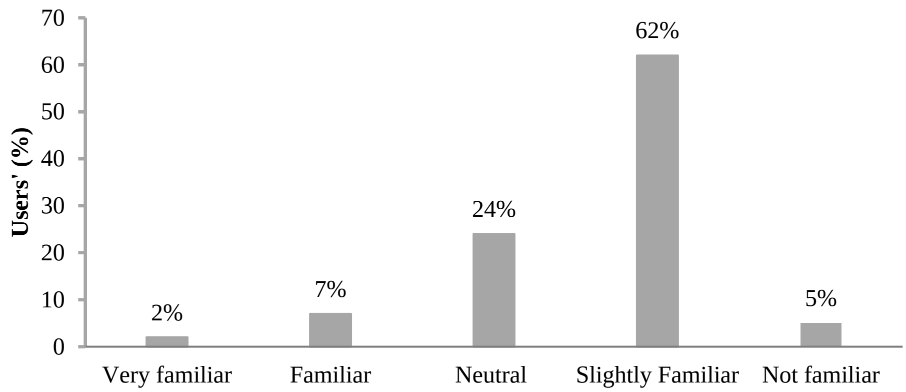


Figure 96. Users' familiarity with green roof systems.

6.3.2 Real-Time Data Acquisition and Analysis

This section presents real-time data acquisition and analysis of plant performance, including plant growth, color, and irrigation system layout. It further outlines data analysis regarding SGR performance and addresses real-time environmental factors.

6.3.2.1 Plant Performance

Pictures of the plants' performance and growth were recorded monthly, shown in Figure 97. The experiment utilized a modular tray SGR system with fresh plants throughout the real-time experiment. It can be seen through visual observations that the plants' conditions were not in a constant state. Plants were slowly underperforming from April 2021 until the beginning of June 2021. However, they reached a healthier state in the following months until November 2021. Due to real-time experimental adjustments, discussed below, there was an evident change and progression for plant survival in hot arid regions, despite July 2021 being noted as the peak of the hottest temperatures of Qatar throughout the year, rising to 42°C. In the September and October 2021 months, plants had considerably flourished with more life, vibrance, and growth.

As a result of a temperature drop as low as 32°C, the plants experienced ease in growth and liveability. Another decrease in plant performance was noticed from November 2021 to the beginning of December 2021 due to considerable and abrupt seasonal changes in weather conditions from summer, an average of 35°C, to winter, an average of 25°C. January and February of 2022 were more favorable to plant conditions, with an overall improvement in plant liveliness. In each state of identified plant performance decline, necessary interventions and adjustments were implemented, including removing dying plants, adding new plants, adding fertilizers, removing an end cap, replacing the drip line, and changing the irrigation system type and layout.

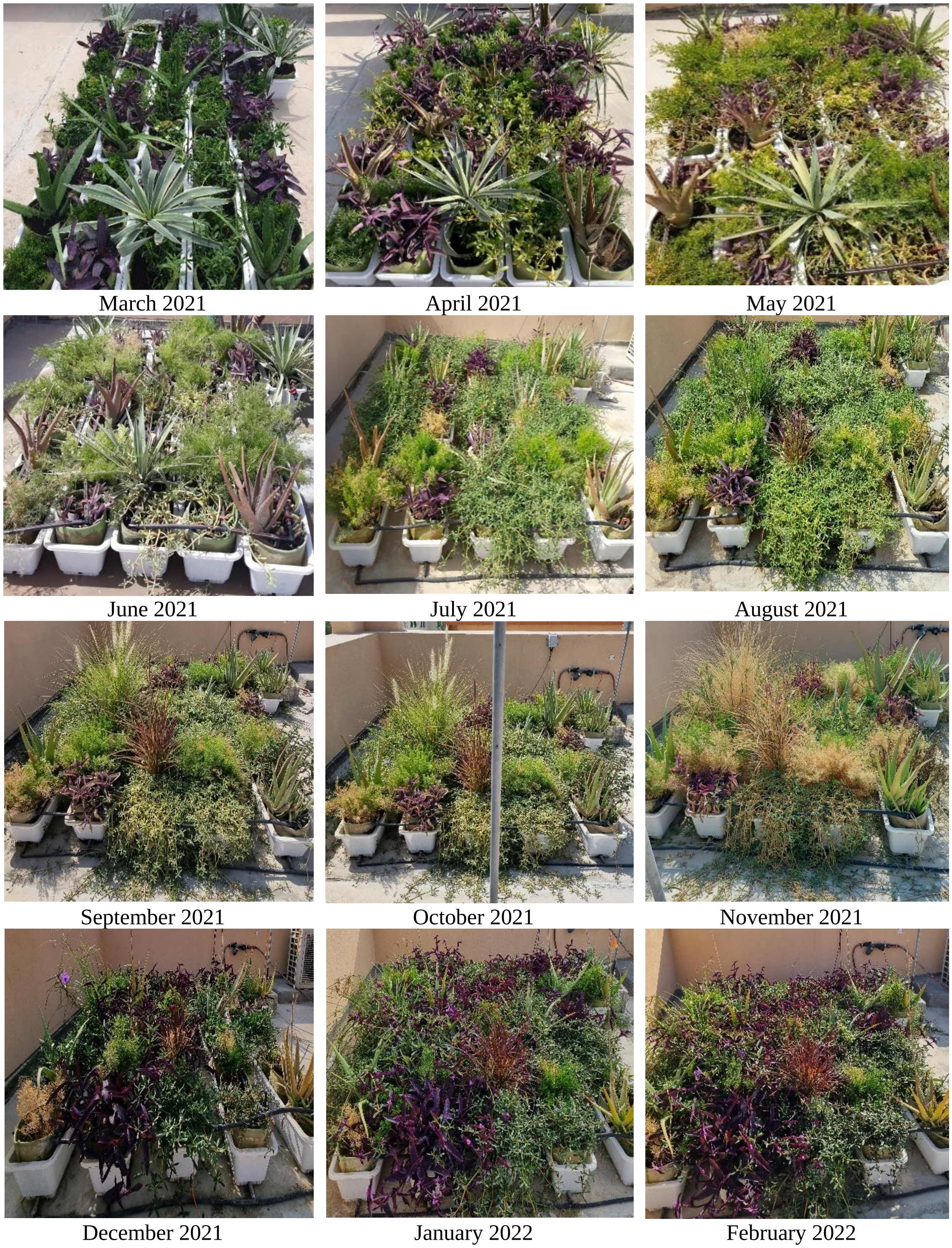


Figure 97. Visual analysis of smart green roof plant's performance monthly.

The real-time experiment was initiated on the 1st of March in 2021, with the plants podded and arranged as depicted in Figure 98. The selection of these native plants was decisive as to their ability to endure and survive in Qatar’s climatic conditions.

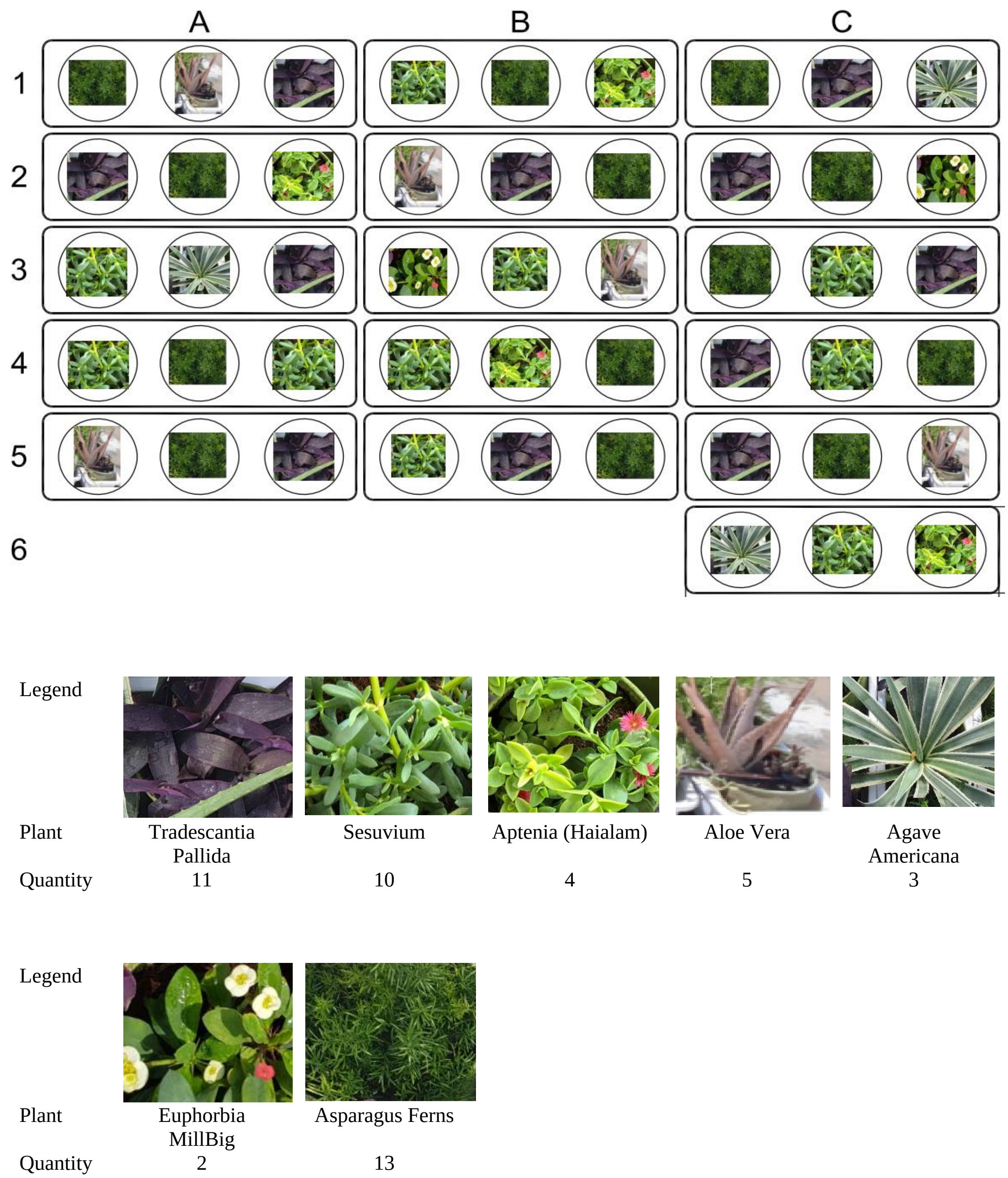


Figure 98. Initial podded plant arrangement in the SGR with the quantity per plant type.

All 48 plants of the SGR were affected by Qatar's harsh climate beginning on 12 June 2021. To counteract the damage, several measures were actioned. One such measure to aid these plants was their maintenance via trimming and the addition of fertilizers to sustain the plants and ensure sustainability. However, despite efforts to enhance the performance of plants, as per recommendations and consultations from experts in the field of landscaping, nine plants' conditions did not improve for several reasons. Namely, the temperature is hot, with arid conditions and high humidity. However, it is critical that throughout the experiment, the Aloe Vera, a native drought resident, has best withstood the high temperatures and full sun exposure compared to the other plant types. Having begun with just five plants, and due to its performance, a further two Aloe Vera plants were added to the SGR.

In particular, nine plants were significantly failing: two Tradescantia Pallida, one Agave Americana, four Aptenia (Haialam), and two Asparagus Ferns. The Tradescantia Pallida leaves fallen off drastically; Agave Americana had developed deep pale wrinkles and bent unhardened leaves; Aptenia (Haialam) appeared droughted and shriveled with dead edges and flowers; and the Asparagus Ferns leaf color had regressed from yellow to brown ash ferns. These observed deteriorations occurred mainly during early to mid-June 2021, from the 10th to the 25th. Fifteen days of summer heat and humidity impacted the plant's color and growth.

A decision to replace them with native plants that adapt to hot arid regions was made. These new plants were planted on the 18th of July 2021, based on literature and landscaping engineering experts' advice to replace the dying plants with new ones. Purposefully, a selection of three Sesuvium, one Ruellia Brittoniana, one Red Pennisetum

Setaceum ‘Rubrum’, one Eremophila Maculata, one Green Pennisetum Setaceum, and two Aloe Vera plants. Figure 99 illustrates this new podded plant layout.

Figure 99. Arrangement of 48 plants with quantity division per type after 18 July 2021; removal and addition of plants.

6.3.2.1.1 Plant color.

A visual observational record of the changes and differences in plant color over the experiment, summarized in Table 35, utilizes an adaptation to Conklin's color classification to describe the state of each plant's condition per month of the experiment; this is to quantify the plant color data. In March and April 2021, the Tradescantia Pallida fell under code (4), showing a dark violet color that is deep and unfading. This shows the plant to be in good condition. By May 2021, the Tradescantia Pallida had relative tints of whiteness, making the plant look pale, weak, and faded, as visually described by code (2). The same pale characteristics were evident in June 2021; however, the color had changed from violet to light brown. This shows a weak and wilting plant in bad condition. After making necessary changes to the irrigation and installation, the damaged Tradescantia Pallida plants (two out of eleven) were replaced with two Pennisetum Setaceum, with the continued maintenance of the remaining nine Tradescantia Pallida plants.

In March 2021, dark and rich green leaves of the Agave Americana were classified under code (4), exhibiting wetness and freshness. The color had faded from dark green to lighter green by April and May 2021, coded as (2). This contributes to showing a less nourished performing plant. By June 2021, the color faded into an even lighter green shade, demonstrating the plant's lowest performance during this month, code (1). One of three Agave Americana plants was desiccated in July 2021 and replaced by Eremophila Maculata.

Following necessary irrigation adjustments, the plants turned from dry, pale, and weak in July 2021 to a rich, dark, and unfading green in August 2021 (codes 3 and 4). The plants began to thrive and blossom in the following months, from September to October

2021. The color range of plants during this time showed consistency, vibrance, and improvement. However, during the sudden transition from a hot to cool climate, as November 2021 began, the plant's color condition quickly deteriorated from a rich dark green to shades of light green, yellow, and brown. In December 2021, plant maintenance, including trimming and fertilizer addition, was scheduled to revive the plants. This tremendously improved the plants achieving a rich deep green and violet, exhibiting wetness and coded (4). In January and February of 2022, the color of most plants maintained a steady, rich, and healthy range, including rich deep, and unfading green, fresh deep shades of maroon, and indelible violet. The coded color classifications of plants from March 2021 to February 2022 correspond to the color range and conditions of plants', providing a quantifiable assessment means for visual observations of the plants.

Table 35. Monthly SGR: coded plant color classification from March 2021-February 2022

Plant Species	**Coded Plant Color Per Month**											
	Mar-2021	**Apr-2021**	**May-2021**	**Jun-2021**	**Jul-2021**	**Aug-2021**	**Sep-2021**	**Oct-2021**	**Nov-2021**	**Dec-2021**	**Jan-2022**	**Feb-2022**
Tradescantia Pallida	4	4	2	2	3	3	3	3	2	4	4	4
Sesuvium	4	4	2	2	3	4	4	4	3	4	4	4
Aptenia (Haialam)	4	4	2	1	Plant died and removed on the 18th of July 2021							
Aloe Vera	4	2	2	2	2	3	3	3	3	4	4	4
Agave Americana	4	2	2	1	3	3	4	4	3	4	4	4
Euphorbia MillBig	4	4	3	2	2	3	3	3	3	4	4	4
Asparagus Ferns	4	4	4	2	3	3	4	4	1	4	4	4
Ruellia Brittoniana	New plant planted on the 18th of July 2021				4	4	4	4	2	3	4	4
Red Pennisetum Setaceum	New plant planted on the 18th of July 2021				4	4	4	3	1	3	4	4
Eremophila Maculata	New plant planted on the 18th of July 2021				4	4	4	4	2	3	4	4
Green Pennisetum Setaceum	New plant planted on the 18th of July 2021				4	4	4	3	1	3	4	4
Average	**4.00**	**3.43**	**2.49**	**1.71**	**3.20**	**3.50**	**3.70**	**3.50**	**2.10**	**3.60**	**4.00**	**4.00**

Moreover, an infrared thermal imaging camera captured the thermal heat signature of plants to understand the plants' influence on the building temperature. As depicted in Figure 100, the more violet color ranges show colder plant temperatures, while the lighter, brighter, warm red, orange, and yellow ranges show hotter plant temperatures (Thermascan, 2019). Hotter temperatures (bright colors) indicate more heat and infrared radiation reflected, while colder temperatures (darker colors) indicate less heat and infrared radiation reflected. Figure 100 shows differing monthly temperature ranges, with better performing thermal heat evident in the last five months, for instance, 19.4°C to 31.4°C in February 2022.

Using the E40 FLIR thermal camera and understanding the amount of radiation absorbed and reflected from the plant, we can understand the effectiveness of plants on the building temperature. Overall, the plants thermal imaging has shown that most plants consistently and effectively absorb heat, thereby reducing heat transfer into the building. Thermal imaging data was unavailable in March and April 2021, as the instrument was only received in May 2021.

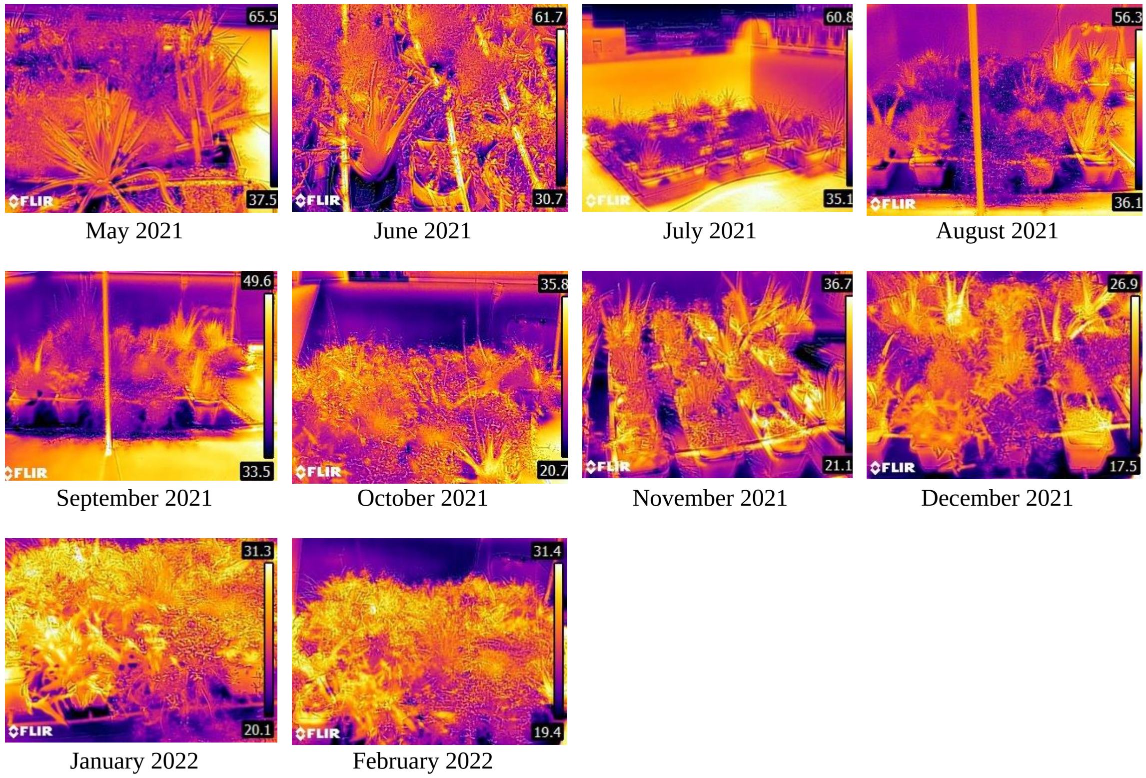


Figure 100. Monthly plants' thermal temperature using an infrared E40 FLIR thermal imaging camera from May 2021 to February 2022.

6.3.2.1.2 Plant growth.

Measuring plant height is essential as it draws conclusive results on plant conditions. Height is a measurable and quantitative phenomenon, and regularly recording height data gives a better understanding of the plant's qualities and conditions. Table 36 compares the quantitative performance of manual vertical height measured during the real-time experiment per month. The following section presents the LAI measurements, measuring the horizontal leaf area coverage. The vegetation height varies between a minimum of 9cm to a maximum of 50cm. Plants exhibiting improvements in height growth include Aloe Vera, Agave Americana, and Pennisetum Setaceum.

Table 36. Monthly Plant height from March 2021-February 2022

Plant Species	Plant Height Per Month (cm)											
	Mar-2021	**Apr-2021**	**May-2021**	**Jun-2021**	**Jul-2021**	**Aug-2021**	**Sep-2021**	**Oct-2021**	**Nov-2021**	**Dec-2021**	**Jan-2022**	**Feb-2022**
Tradescantia Pallida	21	19	14	12	14	16	18	18	12	15	16	16
Sesuvium	12	12	10	10	10	12	12	13	10	11	15	16
Aptenia (Haialam)	16	15	10	9	The plant died and was removed on the 18th of July 2021							
Aloe Vera	29	27	27	27	27	28	28	28	28	40	50	50
Agave Americana	25	24	22	22	24	25	27	27	27	27	30	32
Euphorbia MillBig	17	19	15	15	15	16	16	17	13	15	18	18
Asparagus Ferns	25	22	18	18	22	23	23	25	18	21	22	21
Ruellia Brittonian	New plant planted on the 18th of July 2021				22	22	24	24	20	21	25	22
Red Pennisetum Setaceum	New plant planted on the 18th of July 2021				25	25	30	35	30	35	40	42
Eremophila Maculata	New plant planted on the 18th of July 2021				18	19	22	22	18	20	25	26
Green Pennisetum Setaceum	New plant planted on the 18th of July 2021				30	30	30	35	25	30	45	43
Average	**20.71**	**19.71**	**16.57**	**16.14**	**20.70**	**21.60**	**23.00**	**24.40**	**20.10**	**23.50**	**28.60**	**28.60**

The leaf area index (LAI) is the plant's leaf area ratio to its ground area (Hewitson, 2021). LAI measurements, typically between 0.5-5.0, were taken monthly throughout the experiment (Figure 46). Throughout the months from March to April 2021, the LAI slightly increased. However, the LAI steadily decreased following the months from May to the end of June 2021. Specifically, nine plants were affected, including the Tradescantia Pallida, Agave Americana, Aptenia (Haialam), and Asparagus Ferns. After necessary changes to the irrigation system and plant layout, the LAI increased significantly during July and August 2021, with a rate of increase in LAI in September 2021. The plants illustrated better plant condition, growth, and overall improvement. September and October 2021 show incremental increases in LAI and plant improvement. However, due to the harsh temperature drop, cloudy skies, and limited direct sunlight, LAI and plant growth ceased and became unfavorable in November 2021. The following month December 2021, plants had greatly adjusted to weather conditions with an increase in LAI and newly blossomed flowers. During January and February of 2022, the plants LAI doubled, notably the Tradescantia Pallida, Asparagus Ferns, Sesuvium, Euphorbia MillBig, Pennisetum Setaceum, and Eremophila Maculata plants. Figure 101 shows that the least dense plants with an LAI value recorded at ~0.15 were found throughout November 2021, and the densest LAI of ~2.2 was observed in February 2022.

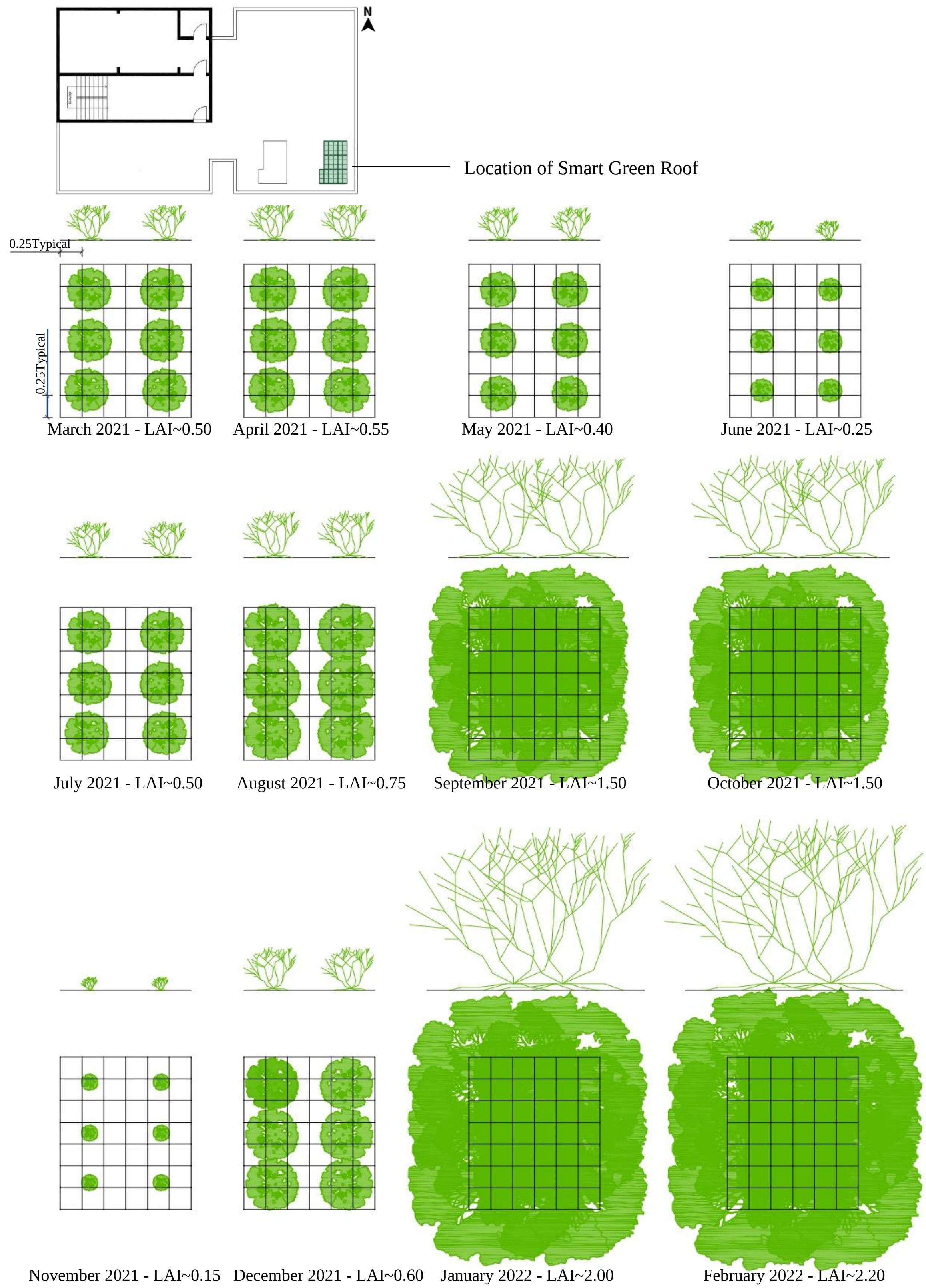


Figure 101. Monthly leaf area index values from March 2021 to February 2022.

6.3.2.2 Irrigation System Layout

Over two months, March and April 2021, manual irrigation was the sole watering for the plants, occurring every second day. Due to this manual watering technique, many negative outcomes resulted from a higher water concentration. From May onward, smart, sustainable drip irrigation was adopted.

For the success of this project, the existing drip line pipe, Netafim Uniram, was deemed unfit for irrigation based on the advice provided by landscape engineers. On 21 June 2021, it was replaced with a new pipe to ensure the plants received equal water, and the drip line outlets remained 20cm apart. The smart Rain Bird drip line pipe system, Xerigation landscape drip emission device (model: barb inlet x barb outlet → XB-20PC: Red), was kept at a flow rate of 7.57 liters per hour. This new drip line was incorporated primarily to distribute the water evenly among all pods and accommodate the plants after moss growth.

Apart from Qatar’s weather, another factor influencing poor plant performance was the gradual moss growth on the vigoroot geotextile wicking fabric due to the soil and plastic pod's excess water (Figure 102). The water build-up occurred because the end cap was still in place. Using a brush and cold water, the moss was gently scrubbed, and the pod was cleaned.

Figure 102. Pod moss growth over the wicking material.

Plant conditions became poor on the 12th of June 2021 due to the hot and humid weather conditions, mainly due to the water being collected and kept inside the plastic pod. The pods were designed deliberately with the inclusion of an end cap at the base of each pod to allow for the collection of water in the pod and facilitate the plant to exhibit capillary action where water uptake via the roots would travel up to the leaves of the plants through an upward movement. However, this increased water volume damaged the plants; therefore, the end cap of the plastic pod was removed to allow the excess water to escape (Figure 103).

Figure 103. Removing the end cap of the plastic pod due to water excess.

Synchronously, water run-off occurred due to removing the end cap. This resulted in a drainage system solution being put in place. To avoid damaging the building structure, a drainage pipe was connected to the bottom of the pods to connect to the drainage outlet (Figure 104).

Figure 104. New pipework and drainage system.

After removing the end caps from all plastic pods and including a drainage system, fertilizers were integrated as maintenance measures to sustain plant growth and functionality. The following two fertilizers were added on the 12th of June 2021:

1. GROViTA 12-12-17 (Granular NPK Fertilizer): 12% total nitrogen (N), 12% ammonium (NH_4), 12% phosphorus pentoxide (P_2O_5), 17% potassium oxide (K_2O), 35% sulfite ion (SO_3), and 14.04% sulfur (S);
2. Solinure 20-20-20+TE (EC Fertilizer – NPK Fertilizer with micro-nutrients, bled, 20-20-20): 20% total nitrogen (N), 20% phosphorus pentoxide (P2O5), and 20% potassium oxide (K2O).

A final adjustment measure to the layout of the SGR plants, to space them out at 20cm horizontally and vertically between each pod, was made on the 18th of July 2021. Expanding the distance between the pods served the purpose of allowing the plants to grow and cover more of the roof area. An event summary, encapsulated in Table 37, outlines key information regarding significant changes and modifications made throughout the real-time data acquisition and analysis.

Table 37. Table summarizing series of events

Date	Event
01 March 2021	Plants planted
01 March 2021	Manual irrigation
01 May 2021	Installation of smart irrigation
10 June 2021	Moss growth – solution: removing the end cap
12 June 2021	Maintenance of plants (trimming and fertilizer added)
21 June 2021	The irrigation pipe was changed, and the drainage system added
18 July 2021	Removed nine failing plants, added nine new plants, and pods spaced at 20cm
15 November 2021	Maintenance of plants (trimming and fertilizer added)

The soil moisture and soil temperature are graphed in Figure 105. Soil temperature levels are measured in degrees Celsius and slowly increase from 34°C in May 2021 to 38°C in July 2021, followed by a sharp decrease over seven months to 19°C in February 2022. In contrast, moisture levels experienced two peaks with significant dips, one at 53.86% in June 2021 and another at 50.42% in September 2021. Following each incline, a steep humidity level decline can be perceived within a month, reaching 47.61% in July 2021 and a more significant dip of 36.90% in October 2021, respectively.

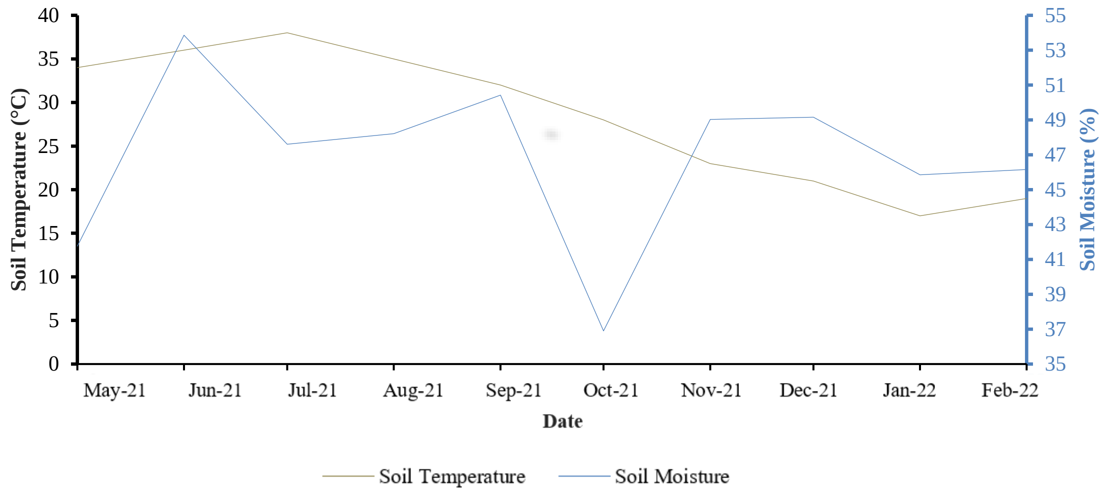


Figure 105. Soil temperature and soil moisture of the SGR from 1 May 2021 to 28 February 2022.

Water volume values shown in Table 38 after integrating smart irrigation were calculated using the formula proposed in the methods section. The smart irrigation system was more effective regarding water sustainability than manual irrigation. The water consumption, as a result of manual irrigation from March 2021 to April 2021, was measured at a total of 2374L and an average of 1187L. Upon the introduction of the smart irrigation system and its smart soil moisture sensor, the water consumption dropped to an average of 37.04L for the months between May 2021 to February 2022 (Figure 106). The merit of utilizing the smart irrigation system was also notably seen in the summer peak of Qatar during July and August 2021, where water use was recorded at an average of 22.65L. As per the outlined structure of experiments 1 through 4, the water volume used for irrigation of the SGR decreased gradually as the set threshold of the soil moisture was lowered consecutively.

Table 38. Monthly water volume consumption of the smart green roof

Date	System	Total Watering (hour)	Volume (L)
Mar-21	Manual	_	742.00
Apr-21		_	1632.00
May-21	Smart automation - Experiment 1	9.17	69.39
Jun-21	Smart automation - Experiment 2	14.85	112.41
Jul-21	Smart automation - Experiment 3	3.68	27.88
Aug-21		2.30	17.41
Sep-21		3.52	26.62
Oct-21		9.98	75.57
Nov-21	Smart automation - Experiment 4	1.62	12.24
Dec-21		1.18	8.96
Jan-22		1.20	9.08
Feb-22		1.43	10.85

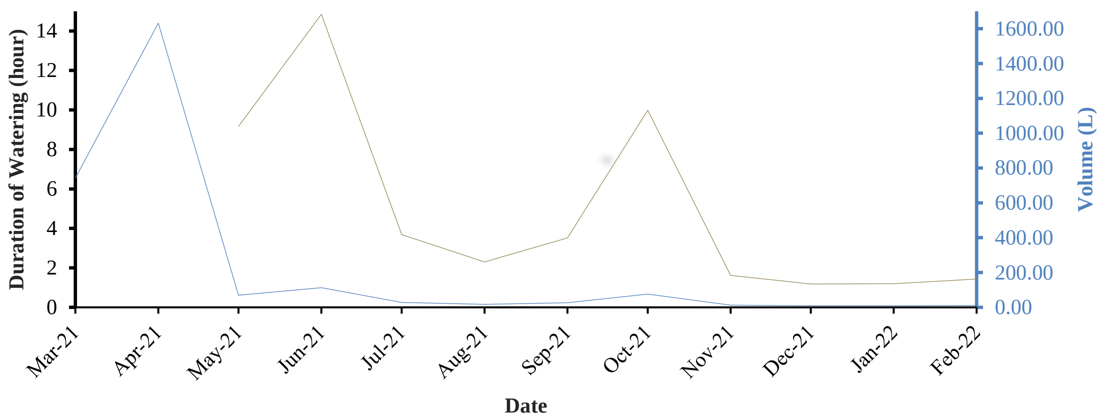


Figure 106. Monthly amount and duration of water consumption for the smart green roof from March 2021 to February 2022.

Moreover, it can be seen in Figure 107 that frequent watering at various times of the day manages to keep the soil moisture level nearly constant. Thus, to limit the amount of water consumed and maintain a more efficient and sustainable smart system, realigning the threshold trigger condition from 45% to 40% from November 2021 to February 2022 was performed.

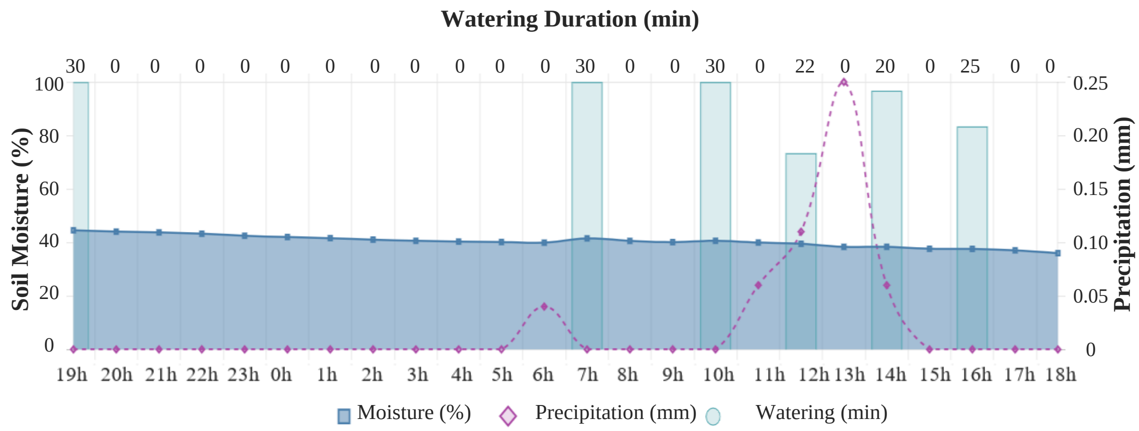


Figure 107. Irrigation cycle.

6.3.2.3 Smart Green Roof Performance Data Analysis

Only with efficient SGR performance, i.e., plant viability and activity, can its effects be seen on building energy consumption and user thermal comfort. Upon thriving plant growth in conjunction with effective smart irrigation, real-time experimental research is considered effective in measuring the true effects of SGR implementation on temperature, humidity, and heat flux. Thus, it is essential to statistically analyze the quantified color, height, and LAI in concurrence with quantifiable irrigation factors, specifically soil moisture, soil temperature, and volume (Table 39). The real-time experiment did not naturally fall into the consecutive winter and summer months. Rather it began over two months of winter (March 2021 and April 2021), followed by six months of summer (May 2021, June 2021, July 2021, August 2021, September 2021, and October 2021), followed by four months of winter (November 2021, December 2021, January 2022, and February 2022), as indicated by the statistics.

Table 39. Statistical analysis for color, height, LAI, soil moisture, soil temperature, and volume during the real-time experiment

	Color (code)	Height (cm)	LAI	Soil Moisture (%)	Soil Temperature (°C)	Volume (L)
Maximum	4.00	28.60	1.50	53.86	38.00	1632.00
Minimum	1.71	16.14	0.15	36.90	17.00	8.96
Mean Winter 1	3.72	20.21	0.53	No data	No data	1187.00
Mean Summer	3.02	20.40	0.82	46.46	33.83	54.88
Mean Winter 2	3.43	25.2	1.24	47.55	20.00	10.28
Mean Winter	3.52	23.54	1.00	47.55	20.00	402.52
Mean	3.72	21.97	0.91	46.98	28.30	228.70
Standard Deviation	N/A	3.96	0.70	4.72	7.45	487.27
Number of Samples	12.00	12.00	12.00	7300.00	7300.00	7300.00

Note. cm, centimeters; LAI, leaf area index; %, percent; °C, degrees Celsius; L, liters; mean winter 1, includes March 2021 and April 2021 months; mean summer, includes May 2021, June 2021, July 2021, August 2021, September 2021, and October 2021 months; mean winter 2, includes November 2021, December 2021, January 2022, and February 2022 months; mean winter, includes March 2021, April 2021, November 2021, December 2021, January 2022, and February 2022 months; no data, smart irrigation began 1 May 2021, so there is no data available to report; N/A, not applicable.

6.3.2.4 Real-Time Environmental Factors

The real-time environmental factors section presents data acquisition and analysis of wind speed, temperature, humidity, and heat flux throughout the experiment, from March 2021 to February 2022.

6.3.2.4.1 Real-time environmental data acquisition.

The real-time data section further entails wind speed, temperature, humidity, and heat flux data. As shown in Figure 108, real-time wind speed measurements are graphed from March 2021 to February 2022. The lowest measurement found was 0m/s, and the highest measure was 8.9m/s. Throughout the experiment, the wind speed constantly fluctuated, with dramatic highs and lows observed in a short period. This great fluctuation in wind speed, from 8.9m/s to 1.5m/s, is highly repetitive and noticeable throughout this experiment.

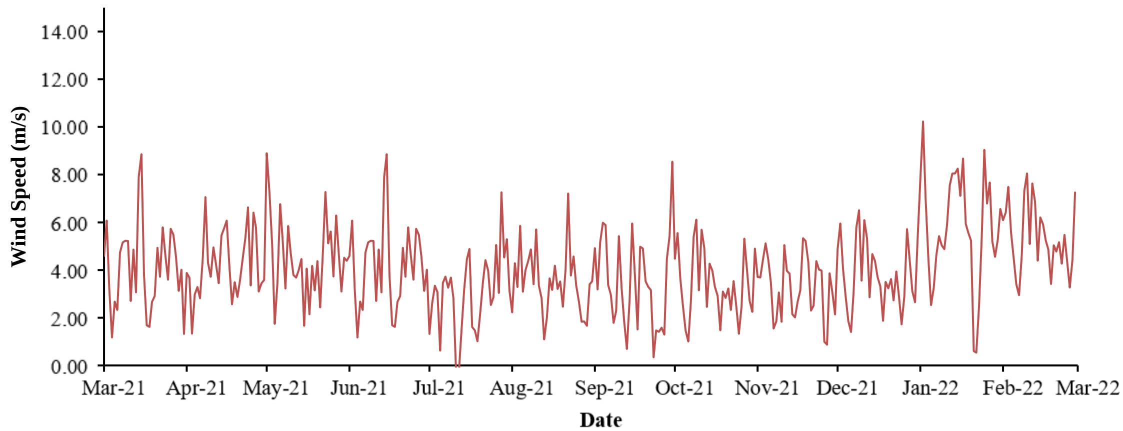


Figure 108. Daily real-time wind speed from 1 March 2021 to 28 February 2022.

Daily real-time relative temperature and outdoor temperature at 1m high for zone 2 bare and SGRs have been recorded in Figure 109. Outdoor bare roof temperature was slightly lower than the relative temperature from March 2021 to April 2021, somewhat higher for the next seven months. Then it reverted to being lower from December 2021 till the end of the experiment. Outdoor SGR temperature results also recorded lower temperatures than outdoor relative and outdoor bare. During the experiment, lower temperatures in zone 2 outdoor temperature SGR were maintained for zone 2 outdoor temperature bare roof.

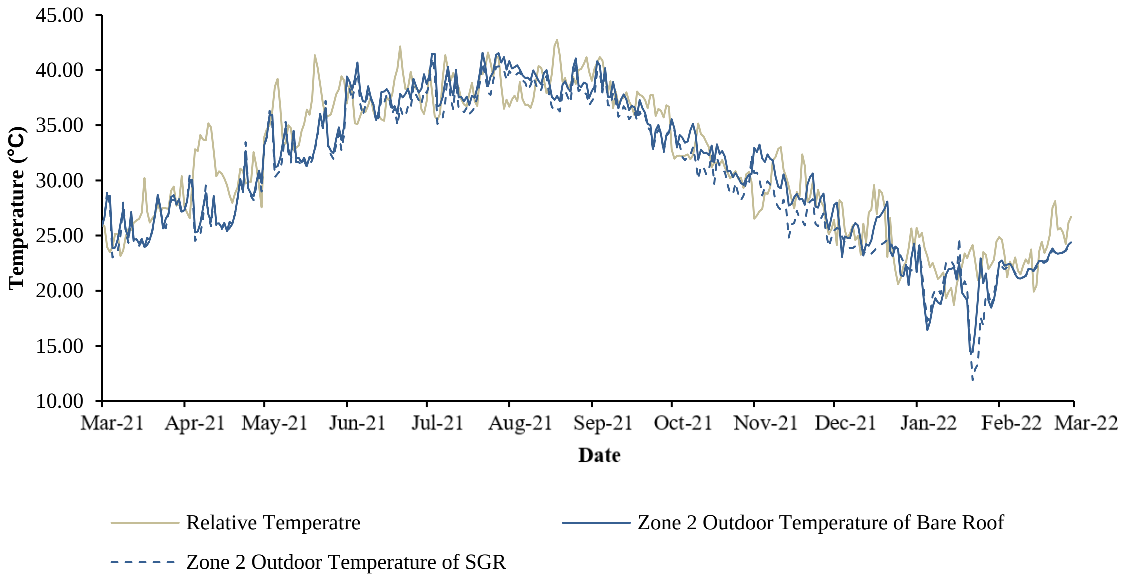


Figure 109. Daily real-time relative temperature and zone 2 outdoor temperature at 1m high from bare and smart green roofs from 1 March 2021 to 28 February 2022.

Note. SGR, smart green roof.

In addition, daily indoor surface ceiling temperature and ambient levels for both bare and SGRs from the real-time experimental zone 2 are delineated in Figure 110. It is noticeable that ambient temperature is mostly lower for indoor SGR. In March 2021, May 2021, June 2021, and January 2022, the bare roof's surface temperature recorded a higher temperature indoors at some intervals, in contrast to a distinctively lower SGR surface temperature. In saying this, the average of these months is lower in terms of temperature level for the SGR than for bare roofs, except for March 2021. Relatively, ambient temperatures of indoor bare and SGR were higher than surface temperatures.

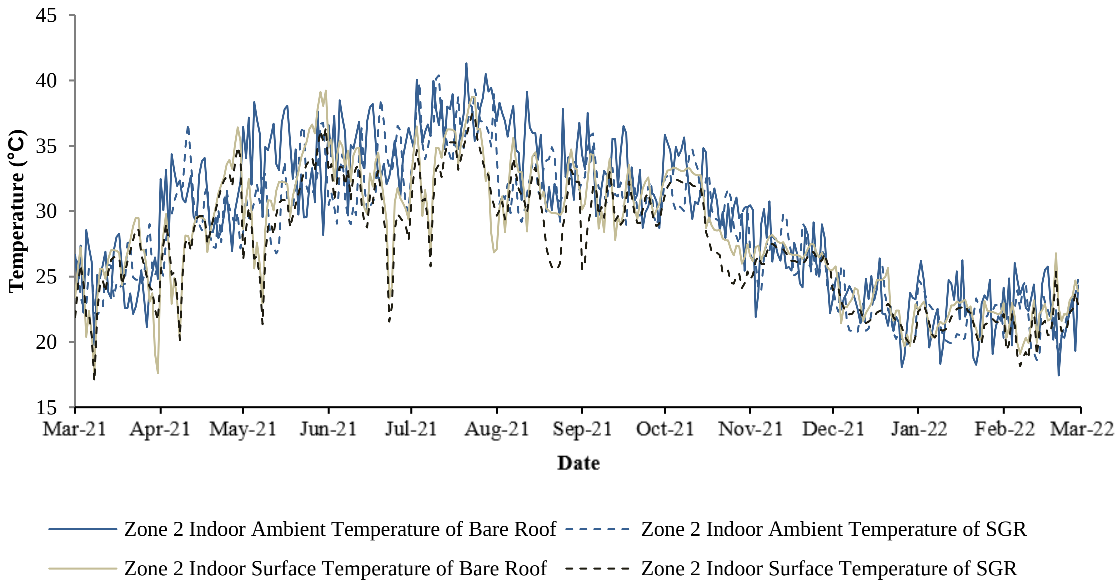


Figure 110. Daily real-time zone 2 indoor ambient temperature and surface ceiling temperature of bare and smart green roofs from 1 March 2021 to 28 February 2022.

Note. SGR, smart green roof.

During this experiment, humidity levels were also measured for both the indoor and outdoor bare and SGRs. The highest percentage reached 80% humidity in both outdoor bare and outdoor SGR during March and April 2021, with the outdoor bare roof usually averaging a slightly higher humidity level than outdoor SGR. The lowest percentage was around 11% humidity for indoor SGR in early March 2021 and 8% humidity for the outdoor bare roof at the end of May 2021. As observed in Figure 111, the humidity levels for indoor bare and indoor SGR were closely adjacent. At the same time, the outdoor bare and outdoor SGR were also closely adjacent with overall lower humidity levels for the indoor SGR. Lastly, the outdoor bare and SGR usually led humidity levels between 40-80%, with a sharp and sudden decrease in May and June 2021 to around 10-30% humidity.

The indoor bare and SGR levels were between 10-70%, slowly increasing humidity levels from June 2021 to January 2022. Overall, it is evident that outdoor bare humidity levels remained higher than indoor bare humidity levels except in June, July, August, and September of 2021. In comparison, humidity levels in the outdoor SGR were elevated in comparison to the indoor values except for the recorded levels in June, August, September, and October of 2021, with a smaller difference between readings.

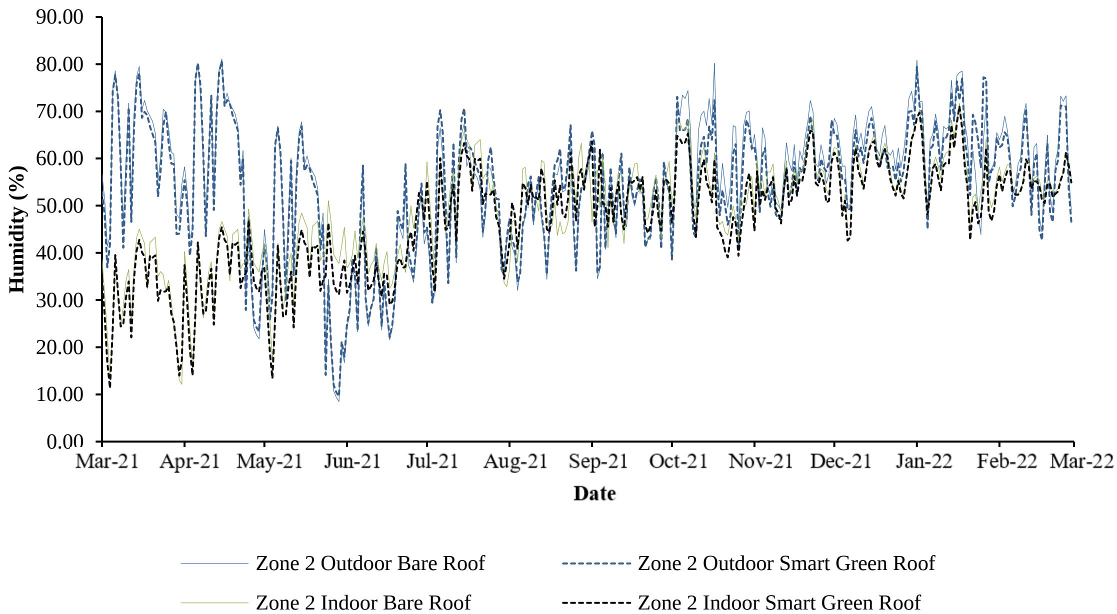


Figure 111. Daily real-time zone 2 humidity level for bare and smart green roofs from 1 March 2021 to 28 February 2022.

During months through the summer and winter seasons, as shown in Figure 112, the measured heat flux and transfer of heat energy were lower in the SGR compared to the bare roof. Considerable heat flux difference between bare and SGR can be noticed from June 2021 to September 2021 and again between October 2021 till December 2021. For instance, November 2021 exhibited the largest difference between bare and SGR heat flux levels, 1.52W/m^2 and 0.46W/m^2, respectively, attributing to around a 75% heat flux decrease as a result of SGR implementation. In contrast, no significant heat flux difference between bare and SGRs during April 2021 was noted, where a steady and equal increase for both was noticed from 0.50W/m^2 to 2.50W/m^2. Lastly, the rate of heat energy passing through bare and SGRs was highest in the summer month, August 2021, reaching around 4.33W/m^2 and 3.54W/m^{2,} respectively; and lowest in winter January 2022, reaching -1.10W/m^2 for both roof types.

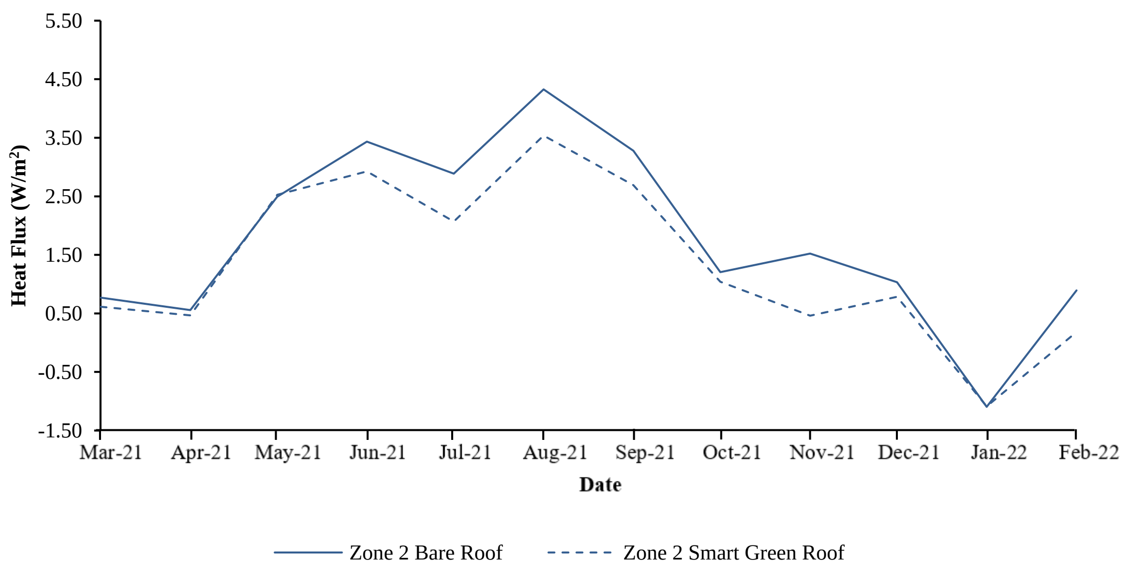


Figure 112. Monthly real-time zone 2 bare and smart green roofs heat flux from March 2021 to February 2022.

6.3.2.4.2 Real-time environmental data analysis.

The above data acquisition values signify a successful real-time research experiment, allowing for efficient statistical analysis and corresponding interpretation of the SGR's effect on temperature, humidity, and heat flux. SGR performance was evaluated by comparing the plants' effects on the environment and the building. This section allows for a better understanding of the green roof plants' influence on reducing heat and energy, improving temperature levels, and enhancing the users' thermal comfort. Assessing the statistical analysis of real-time zone 2 data will help objectify the research dissertation aims (Table 40). The following provides an analytical viewpoint on the influence of plants' performance on humidity, temperature, and heat flux on the bare and SGRs (Tables 41 and 42). To further understand the effect of the SGR, the outdoor and indoor humidity is examined in comparison to the bare roof (Figure 113).

Table 40. Statistical analysis of real-time data: relative temperature and wind speed

	Relative Temperature (°C)	**Wind Speed (m/s)**
Maximum	42.75	10.23
Minimum	18.71	-0.37
Mean Winter 1	28.58	4.30
Mean Summer	36.82	3.68
Mean Winter 2	25.09	4.56
Mean Winter	26.25	4.48
Mean	31.58	4.05
Standard Deviation	6.21	1.79
Number of Samples	17520	17520

Note. °C, degrees Celsius; m/s, meters per second; mean winter 1, includes March 2021 and April 2021 months; mean summer, includes May 2021, June 2021, July 2021, August 2021, September 2021, and October 2021 months; mean winter 2, includes November 2021, December 2021, January 2022, and February 2022 months; mean winter, includes March 2021, April 2021, November 2021, December 2021, January 2022, and February 2022 months.

Table 41. Statistical analysis of real-time zone 2 data: outdoor humidity, outdoor temperature at 1m height, indoor measurements, and heat flux for bare and smart green roofs

	Zone 2 Bare Roof						**Zone 2 Smart Green Roof**					
	Outdoor Humidity (%)	**Outdoor Temp at 1m high (°C)**	**Indoor Humidity (%)**	**Indoor Ambient Temp (°C)**	**Indoor Surface Ceiling Temp (°C)**	**Heat Flux (W/m^2)**	**Outdoor Humidity (%)**	**Outdoor Temp at 1m high (°C)**	**Indoor Humidity (%)**	**Indoor Ambient Temp (°C)**	**Indoor Surface Ceiling Temp (°C)**	**Heat Flux (W/m^2)**
Maximum	81.10	41.58	71.66	41.31	39.23	4.33	80.64	41.15	71.07	40.39	37.42	3.54
Minimum	8.48	14.43	12.15	17.44	17.61	-1.10	9.59	11.88	11.30	18.61	16.98	-1.09
Mean Winter 1	59.78	28.22	34.50	27.84	27.07	0.67	58.23	28.00	32.50	27.42	26.77	0.55
Mean Summer	48.50	36.95	48.34	34.12	31.88	2.94	48.51	36.16	46.33	32.58	30.55	2.47
Mean Winter 2	62.50	22.60	56.90	23.64	23.68	0.59	60.16	21.02	55.83	23.15	21.55	0.01
Mean Winter	61.14	26.34	47.94	25.04	25.04	0.61	59.20	24.51	44.17	24.57	23.64	0.19
Mean	54.90	30.82	48.93	29.62	28.32	1.78	54.05	30.11	47.11	28.62	27.36	1.35
Standard Deviation	14.03	6.62	11.13	5.67	4.88	1.53	13.45	6.48	11.51	5.11	4.58	1.37
Number of Samples	17520	17520	17520	17520	17520	17520	17520	17520	17520	17520	17520	17520

Note. Temp, temperature; °C, degrees Celsius; %, percent; W/m^2, watts per square meter; mean winter 1, includes March 2021 and April 2021 months; mean summer, includes May 2021, June 2021, July 2021, August 2021, September 2021, and October 2021 months; mean winter 2, includes November 2021, December 2021, January 2022, and February 2022 months; mean winter, includes March 2021, April 2021, November 2021, December 2021, January 2022, and February 2022 months.

Table 42. Mean differences of real-time zone 2 bare roof vs. smart green roof during summer and winter

	Zone 2 Bare Roof vs. Smart Green Roof					
	Outdoor Humidity (%)	**Outdoor Temp at 1m high (°C)**	**Indoor Humidity (%)**	**Indoor Ambient Temp (°C)**	**Indoor Surface Ceiling Temp (°C)**	**Heat Flux (W/m^2)**
Mean Difference in Summer	-0.01	0.79	2.01	1.54	1.33	0.47
Mean Difference in Winter	1.94	1.83	3.77	0.47	1.40	0.42

Note. Temp, temperature; m, meter; °C, degrees Celsius; %, percent; W/m^2, watts per square meter; mean difference in summer, includes May 2021, June 2021, July 2021, August 2021, September 2021, and October 2021 months; mean difference in winter, includes March 2021, April 2021, November 2021, December 2021, January 2022, and February 2022 months.

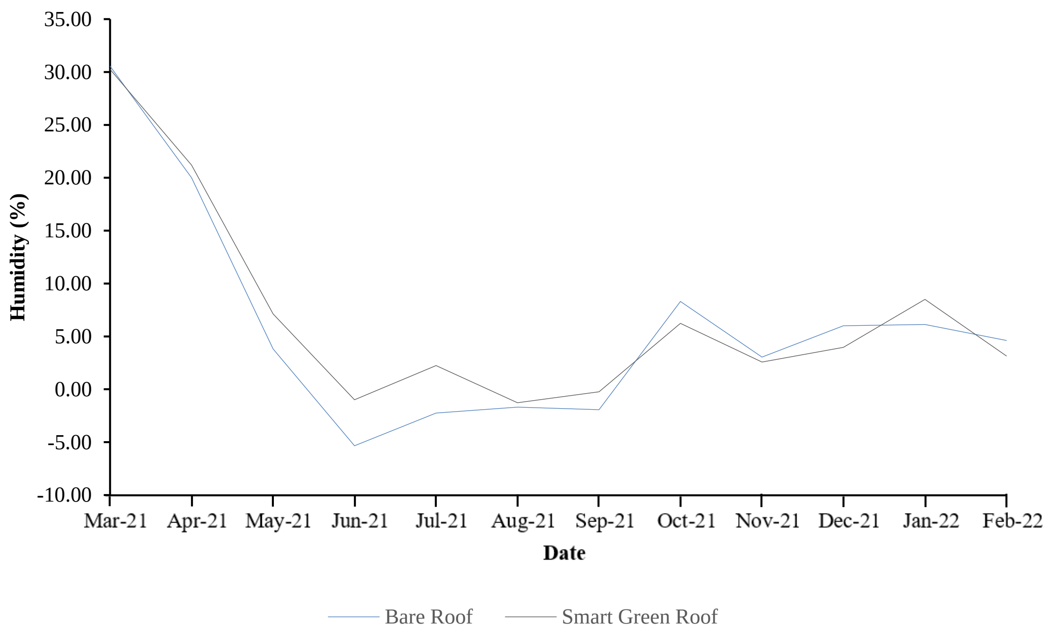


Figure 113. Difference of outdoor and indoor humidity for bare and smart green roofs.

Further corroborating the efficiency of the SGR developed on the office building in Qatar, the differences achieved by its use for outdoor humidity, outdoor temperature at 1m height, indoor ambient temperature, heat flux, and particularly for indoor humidity, and indoor surface ceiling temperature are prevalent. Indoor surface ceiling temperature decreased and improved within the confines of the SGR use, resulting in lower summer and winter means by 1.33ºC and 1.40ºC, respectively (Table 42). Heat flux, a factor measuring the rate of heat energy passing through the roof surface to zone 2, was limited with the SGR by 0.47W/m^2 and 0.42W/m^2 in summer and winter, respectively (Table 42). This is as hypothesized, as SGRs have been found to reduce the heat flux passing through surfaces. In support, a lower mean difference was achieved by SGR implementation for indoor surface ceiling temperature.

There is a diverse range of environmental factors that are affected by the plant performance parameters of an SGR. Statistical significance needs to be established to understand better an SGR's role and the type of effects they elicit. Figures 114, 115, 116, 117, and 118 show the prominence of which two factors together are highly likely to be correlated in the absence of randomness, indicating an integrated successful performance between plant parameters and environmental factors.

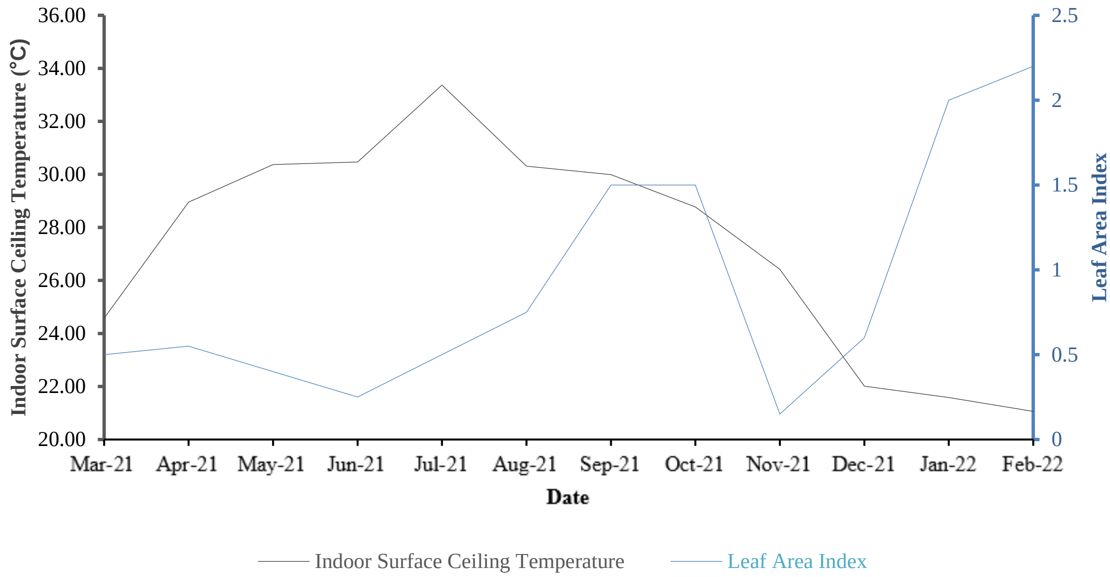


Figure 114. Real-time zone 2 smart green roof indoor surface ceiling temperature and leaf area index.

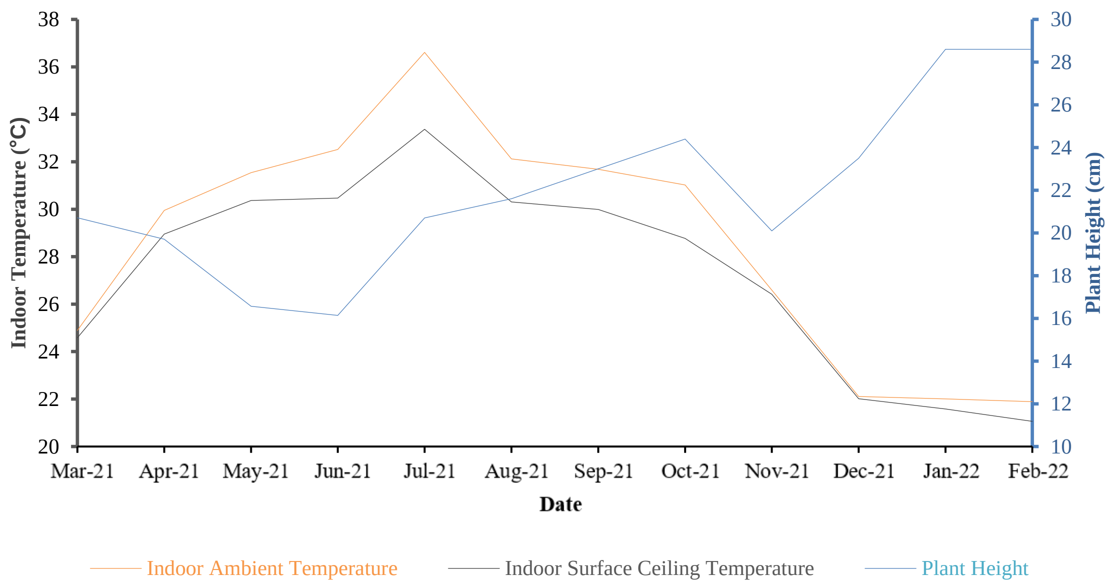


Figure 115. Real-time zone 2 smart green roof indoor ambient temperature, indoor surface ceiling temperature, and plant height.

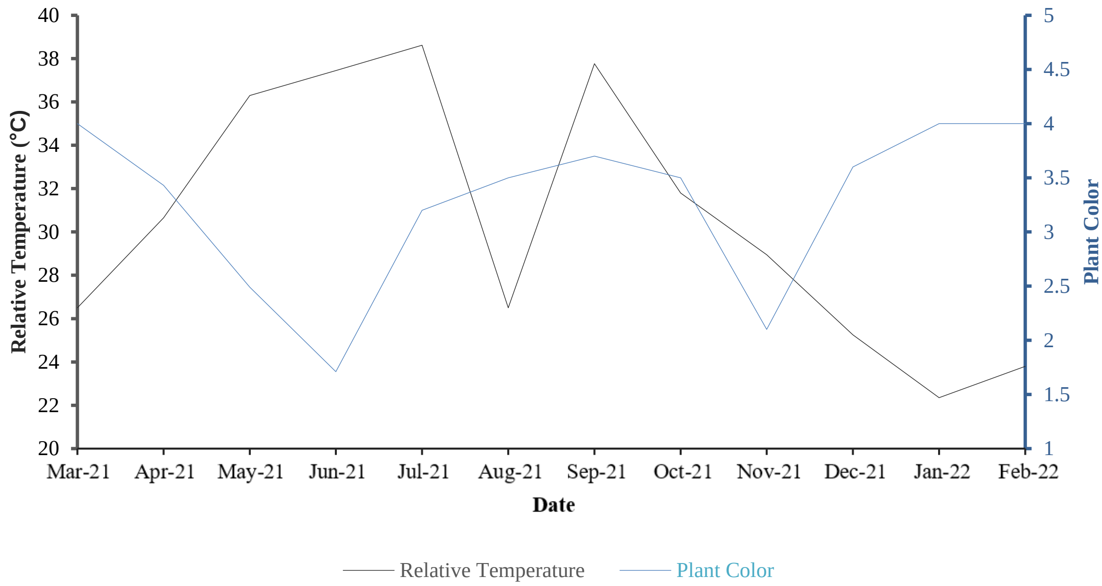


Figure 116. Real-time zone 2 smart green roof relative temperature and plant color.

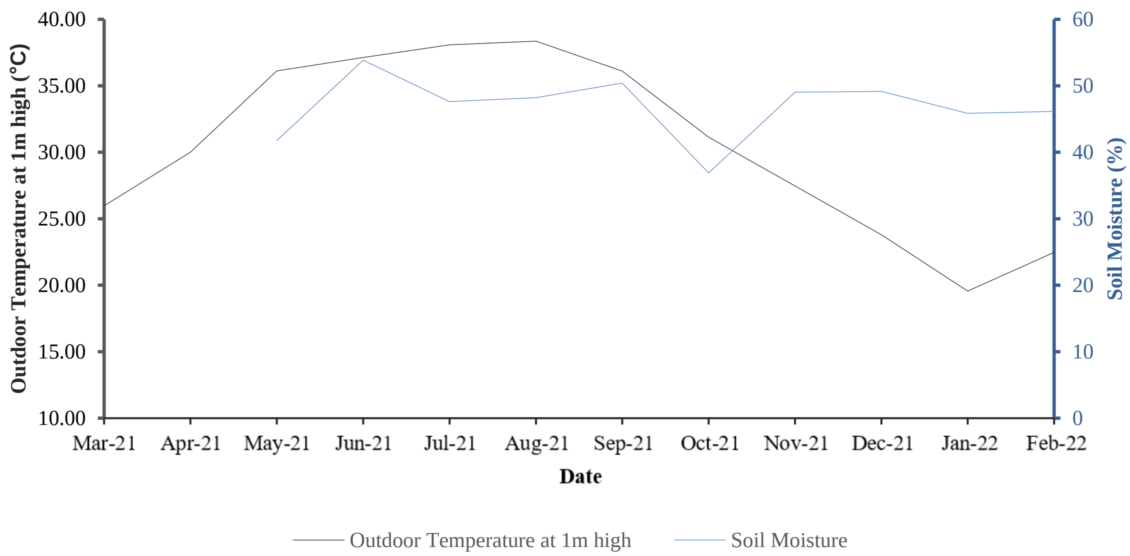


Figure 117. Real-time zone 2 smart green roof outdoor temperature at 1m high and soil moisture.

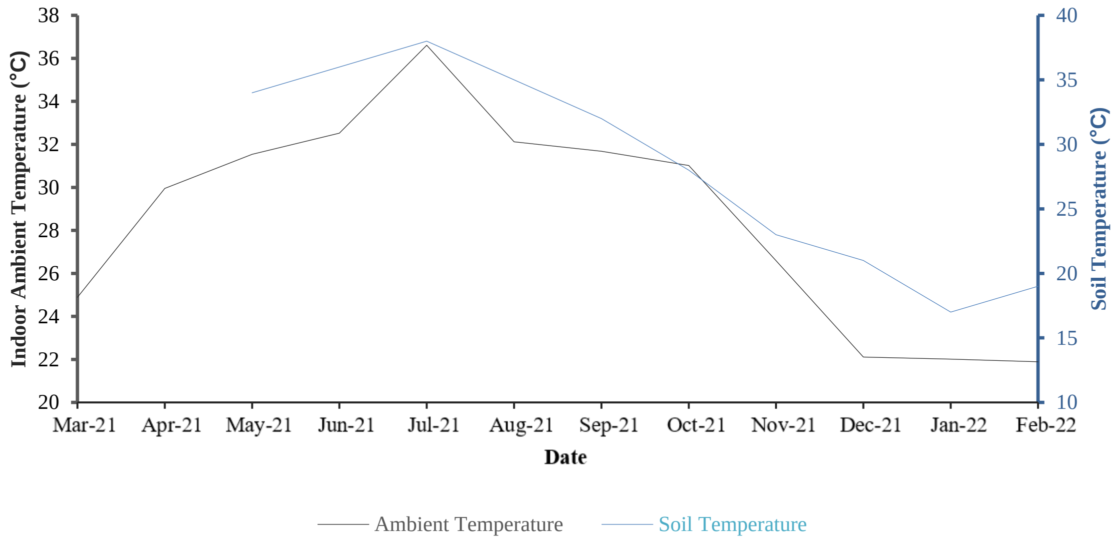


Figure 118. Real-time zone 2 smart green roof indoor ambient temperature and soil temperature.

The above five figures correspond to the below *p* values, presented in Table 43, showing a statistical significance between environmental factors against experimented plant parameters. The ANOVA test is utilized to determine whether the experimental mean results are statistically significant, reliable, and not due to chance. However, indoor surface ceiling temperature and LAI, relative temperature and plant color, and outdoor temperature at 1m height and soil moisture, do not fall below the statistical significance threshold defined, corresponding to 10%, 6%, and 6%, respectively. The fact that the experiment did not employ smart irrigation throughout may have accounted for these probabilities. Therefore, SGR performance was inconsistent and non-optimal for two months, March and April 2021, when manual irrigation was the source of water supply. Despite each of these dual observed results surpassing the threshold by just a few percent, they are essential to the scope of the research objectives, thus, accordingly, will be treated as not occurring by random chance.

Table 43. Statistical significance: *p* values for real-time zone 2 smart green roof environmental factors against plant parameters

Real-time Zone 2 Environmental Factors against Plant Parameters	***p* value**
Indoor surface ceiling temperature and leaf area index	0.10
Indoor ambient temperature and plant height	0.03
Indoor surface ceiling temperature and plant height	0.01
Relative temperature and plant color	0.06
Outdoor temperature at 1m high and soil moisture	0.06
Indoor ambient temperature and soil temperature	0.04

The remainder of this chapter presents the data acquisition, an in-depth statistical analysis investigation of the SGR profile based on simulated data, and further research of the calibration and validation of DesignBuilder.

6.3.3 Simulated Data Acquisition and Analysis

This section presents DesignBuilder's simulated data acquisition of environmental factors and incorporates their data analysis. Along with analyzing data through mean and standard deviation, statistical analysis between environmental factors and plant performance parameters is made using the *p* value tool. It further points to a particular focus on the simulated peak day, where the highest temperature and heat flux readings are modelled.

6.3.3.1 Simulation of Environmental Data

The simulation section includes simulated data regarding temperature, humidity, wind speed, thermal conductivity, U-Value, R-Value, heat flux, and energy demand for zones 1, 2, and 3 of bare roof and SGR.

The meteorological data is presented in Figure 119 and were obtained in Doha, Qatar using DesignBuilder over a month-based period. The data shows the relative temperature, humidity, and wind speed. The relative temperature was low in March 2021, with a gradual increase till August 2021 and a low sloping decrease to January 2022. The lowest relative temperature was 18°C in January 2022, and the highest relative temperature was 43°C in mid-July 2021. On another note, relative humidity ranged from the lowest 25% humidity in mid-June 2021 to the highest 95% humidity level in December 2021. Overall, the humidity levels decreased from March 2021 to July 2021; afterward, humidity percentages began to rise until the end of February 2022. Throughout this experiment, it is noticeable that within shorter periods ranging from a few days to one week, humidity levels sharply increase to around 40% and immediately decrease. Within each month, DesignBuilder generated a high and low wind speed. A high wind speed reached 8.5m/s for an average of 3 months or 4.5m/s for most months. A low wind speed was usually between 2.5m/s and 1m/s for most months. The highest wind speed was in July 2021 at 9.4m/s, and the lowest wind speed was in September 2021 at 0.5m/s. For most months, wind speed averaged around 3m/s to 4.5m/s.

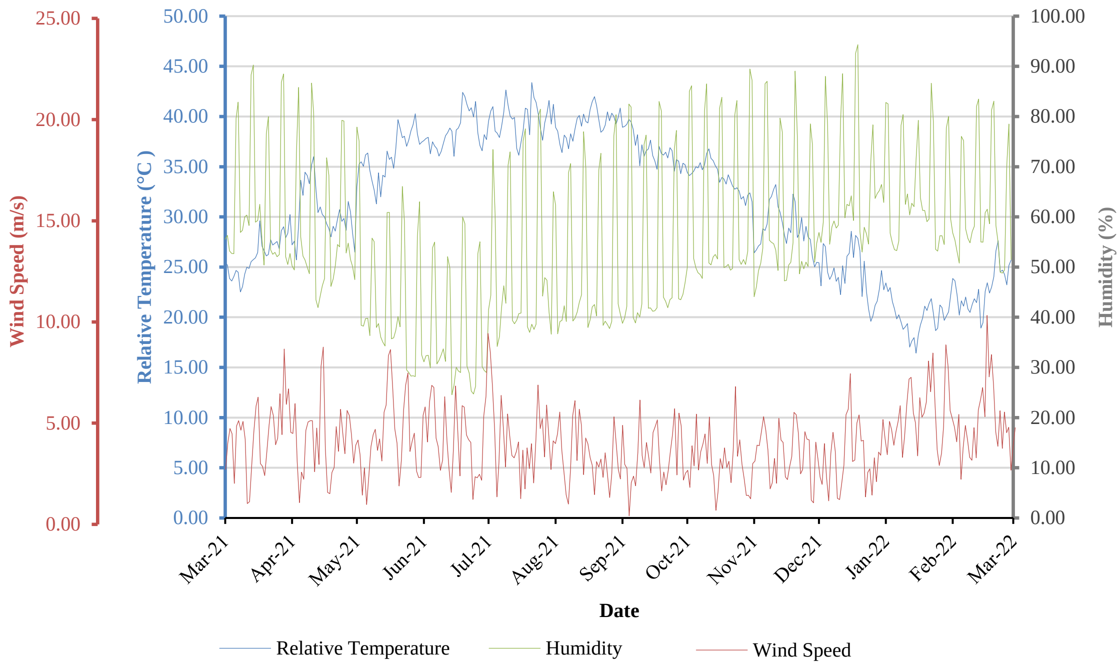


Figure 119. Qatar's meteorological simulated data in DesignBuiler, for daily relative temperature, humidity, and wind speed, from 1 March 2021 to 28 February 2022.

Figures 120, 121, and 122 illustrate the daily extracted indoor surface temperatures of bare roofs and SGRs for zones 1, 2, and 3 from DesignBuilder. Zone 1 bare and SGR surface temperatures are estimated to be mostly within the same temperature level, with higher temperature levels during summer (March 2021-July 2021) and lower temperature levels during winter (July 2021-February 2022). This high and low slope captured across seasons with fluctuating temperature levels is similarly reflected in zones 2 and 3. In the case of zone 2, bare roof temperature levels are higher than SGR levels, with a temperature difference of around 2°C. In the case of zone 3, bare roof temperature levels are usually higher than SGR levels, with a temperature difference ranging from 1-3°C except from mid-May 2021 to mid-June 2021. During these months, SGR indoor surface temperature was calibrated to be higher than the bare roof temperature in zone 3.

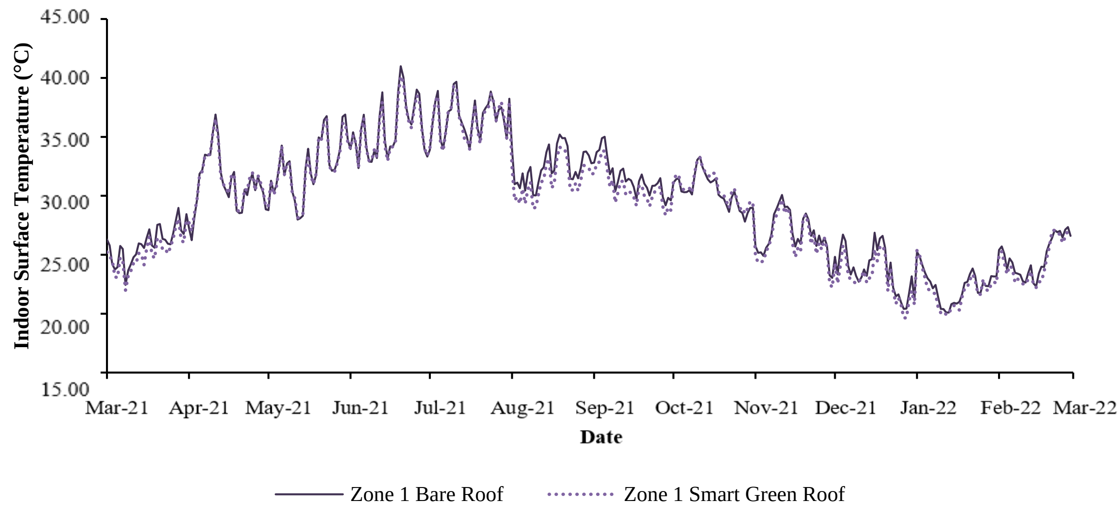


Figure 120. Daily simulated indoor surface ceiling temperature of zone 1 bare and smart green roofs, from 1 March 2021 to 28 February 2022.

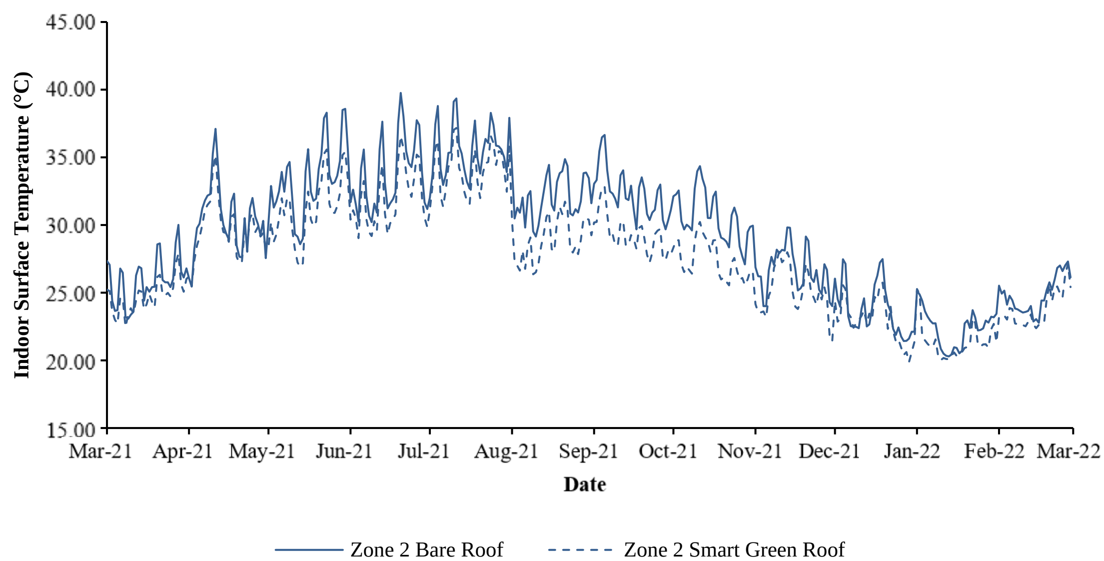


Figure 121. Daily simulated indoor surface ceiling temperature of zone 2 bare and smart green roofs, from 1 March 2021 to 28 February 2022.

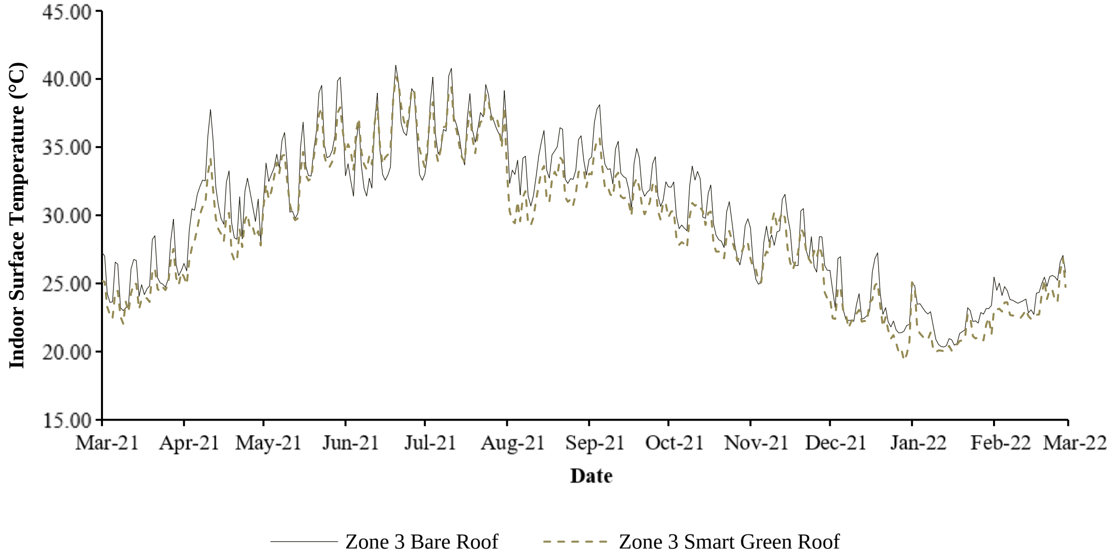


Figure 122. Daily simulated indoor surface ceiling temperature of zone 3 bare and smart green roofs, from 1 March 2021 to 28 February 2022.

DesignBuilder also estimated the heat flux for both bare and SGRs for zones 1, 2, and 3 (Figure 123). Of all three zones, zone 1 showed the lowest heat flux levels. Zone 1 is the only zone where the bare and SGR heat flux measurements were close and similar, with the greatest amount of low heat flux linear slope consistency than others. It is also the only zone where the bare roof had, for four months from April 2021 to August 2021, lower heat flux transfer than the SGR. In contrast, zone 2 and 3 consistently had lower heat flux in SGRs than bare roofs. Zone 2 SGR's heat flux was always lower than the bare roof's heat flux. From March 2021 to June 2021, the heat flux difference between bare and SGR was not that significant, logging a difference of 0.8W/m^2 at most. In the following months, between July 2021 to January 2022, the heat flux difference apexed at 2.55W/m^2 in November 2021. Most of the time, the incline and decline of heat flux read the same for both bare and SGRs. The highest heat flux for bare roofs from any zone was 4.26W/m^2, and the lowest data point was 0.20W/m^2. The highest heat flux for SGRs from any zone was 2.50W/m^2, and the lowest was -0.03W/m^2. Lastly, a linear consistency in the heat flux was discerned for SGRs in zone 3 from October 2021 to January 2022, averaging at a constant 0.20W/m^2. Zone 3 bare roof had similar heat flux measurements as zone 2 bare roof. In August 2021, the former, zone 3, recorded a high of 3.69W/m^2, while the latter, zone 2, had a higher reading of 4.26W/m^2. Furthermore, zone 3 bare roof heat flux fluctuations have a distinguishing sharp decline from September 2021 of 3.25W/m^2 to 0.74W/m^2 in October 2021 and a nearly linear slope of around 0.66W/m^2 until February 2022. Lastly, the SGRs effect on zone 3 was different than on zone 2, where the heat flux remained at a completely linear slope at an average of 0.13W/m^2 all year round, as opposed to the high heat flux fluctuations of zone 2 SGR.

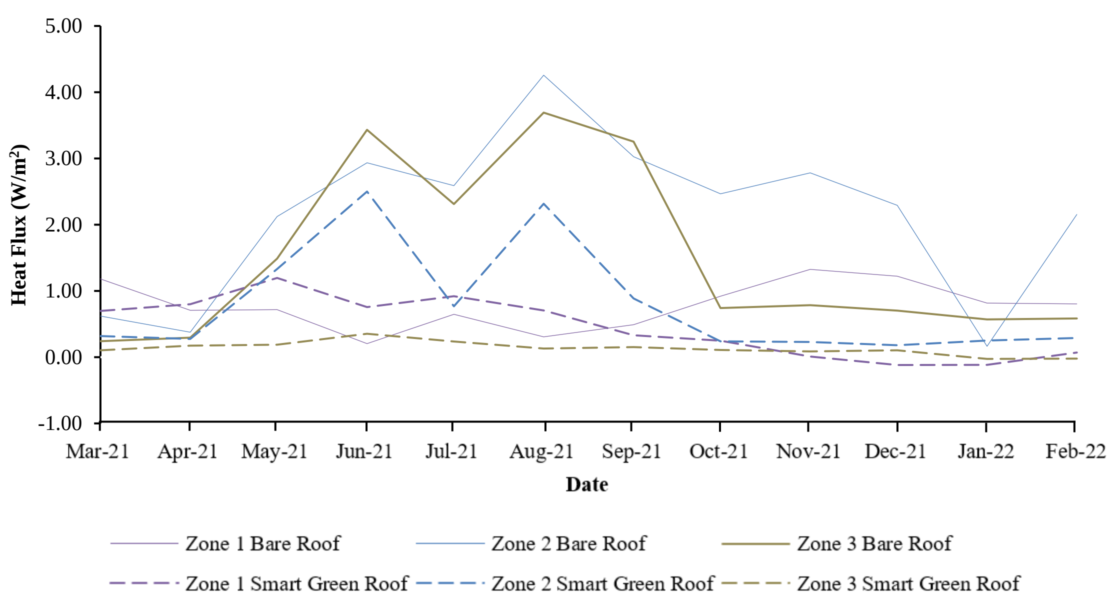


Figure 123. Monthly heat flux of simulated zone 1, 2, and 3 bare and smart green roofs generated from DesignBuilder, from March 2021 to February 2022.

Characteristics of bare and SGRs are detailed in Table 44. The total thickness of the bare roof is 300.00mm, while the SGR is 710.10mm. The LAI value of 2.5 was inputted into DesignBuilder for the SGR to derive the thermal conductivity, U-Value, and R-Value. Thermal conductivity and R-Value are higher for SGR compared to the bare roof. SGR had a 0.31W/mK thermal conductivity and a 2.27m^{2}K/W R-Value; contrastingly, the bare roof had a 0.17W/mK thermal conductivity and a 1.72m^{2}K/W R-Value. Furthermore, the U-Value was higher for bare roofs than SGRs, with 0.58W/m^{2}K and 0.44W/m^{2}K, respectively (Figures 124 and 125).

Table 44. Characteristics of bare and smart green roofs, generated from DesignBuilder

Roof Type	**Total Thickness (mm)**	**Thermal conductivity (W/mK)**	**U-Value (W/m^{2}K)**	**R-Value (m^{2}K/W)**	**LAI**
Bare	300.00	0.17	0.58	1.72	_
Smart Green	710.10	0.31	0.44	2.27	2.50

Note. U-Value, overall heat transfer coefficient; R-Value, thermal resistance; mm, millimeter; W/mK, watts per meter kelvin; W/m^{2}K, watts per square meter, per degree kelvin; m^{2}K/W, meters squared kelvin per watt.

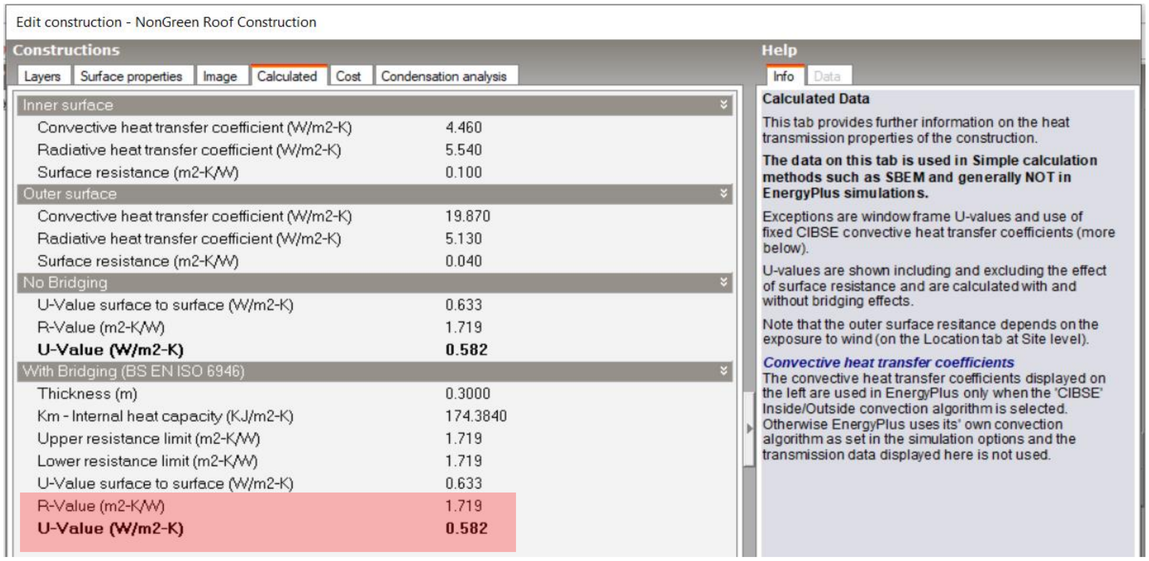


Figure 124. Bare roof calculations of U-Value and R-Value from DesignBuilder software.

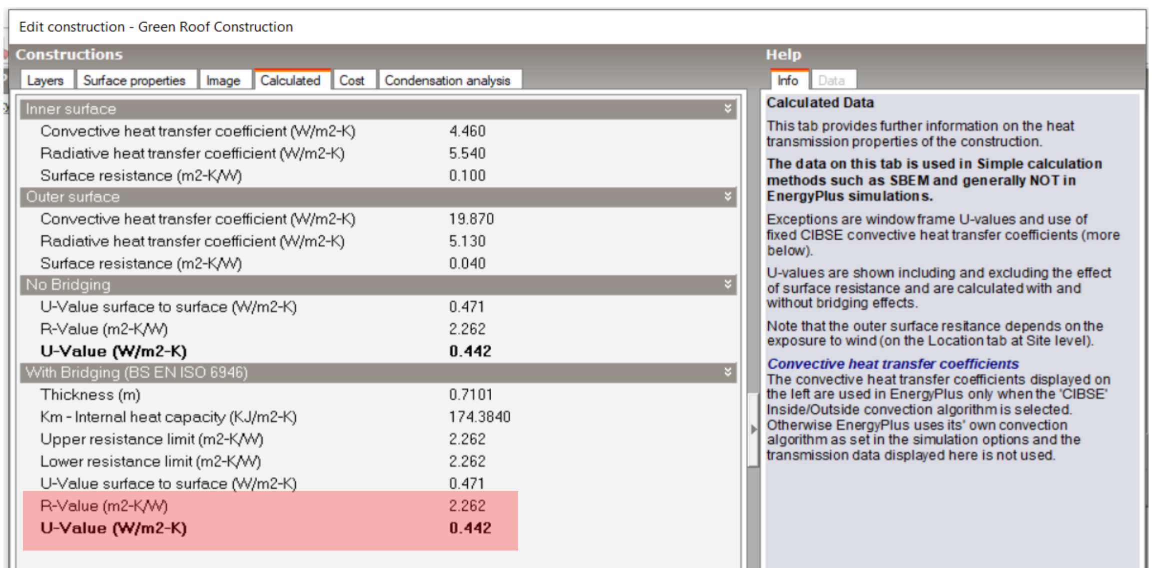


Figure 125. Smart green roof calculations U-Value and R-Value from DesignBuilder software.

Figure 126 identifies the sensible cooling needed per month for zone 1, 2, and 3 bare and SGRs. The highest to the lowest energy consumption of cooling required is zone 3 bare roof, zone 2 bare roof, zone 3 SGR, zone 2 SGR, zone 1 bare roof, and zone 1 SGR, respectively. During summer, particularly in the peak of June 2021, all zone bare and SGRs had their highest need for cooling, reaching heights of 13.68kWh/m^2, 11.68kWh/m^2, 9.86kWh/m^2, 9.36kWh/m^2, 8.12kWh/m^2, and 7.85kWh/m^2. The need for cooling declined in the cooler months, from August 2021 to October 2021 and December 2021 onwards.

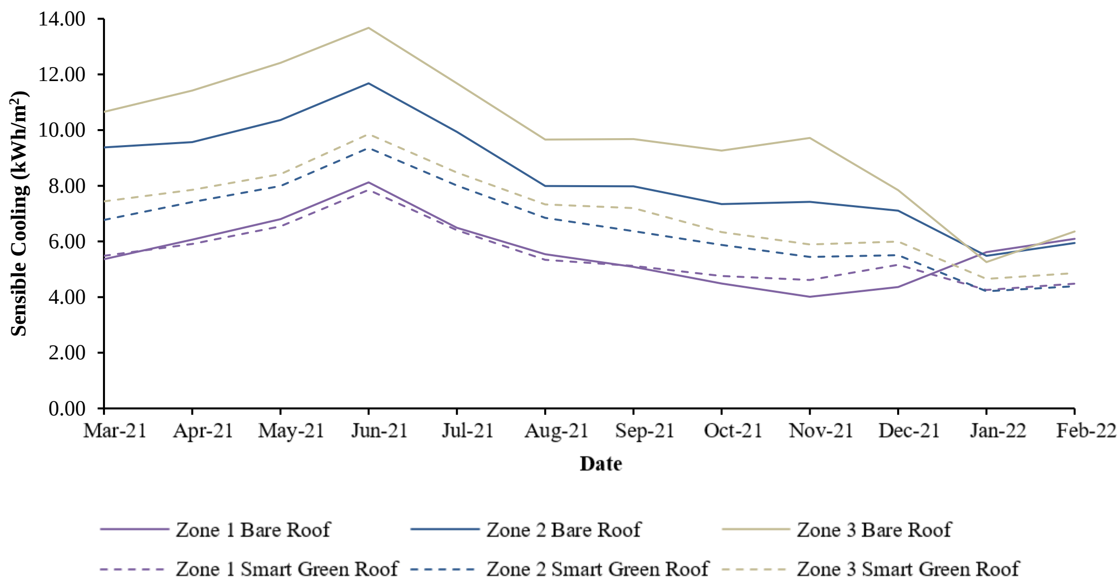


Figure 126. Monthly simulated sensible cooling required for zones 1, 2, and 3 bare and smart green roofs from March 2021 to February 2022.

6.3.3.2 Simulation Data Analysis

The simulation exploits the DesignBuilder software to generate relative temperature, relative humidity, and wind speed findings, as illustrated in Table 45. DesignBuilder simulated data for relative temperature, and wind speed are closely similar to the real-time data presented in Table 45 for relative temperature and wind speed.

Table 45. Statistical analysis of simulated weather parameters

	Relative Temperature DesignBuilder (°C)	Relative Humidity DesignBuilder (%)	Wind Speed DesignBuilder (m/s)
Maximum	43.38	94.31	10.32
Minimum	16.43	24.57	0.42
Mean Winter 1	28.25	59.94	4.25
Mean Summer	37.37	48.88	3.76
Mean Winter 2	24.00	63.00	4.34
Mean Winter	25.43	61.97	4.31
Mean	31.45	55.37	4.03
Standard Deviation	6.90	16.26	1.73
Number of Samples	17520	17520	17520

Note. °C, degrees Celsius; %, percent; m/s, meters per second; mean winter 1, includes March 2021 and April 2021 months; mean summer, includes May 2021, June 2021, July 2021, August 2021, September 2021, and October 2021 months; mean winter 2, includes November 2021, December 2021, January 2022, and February 2022 months; mean winter, includes March 2021, April 2021, November 2021, December 2021, January 2022, and February 2022 months.

This section will evaluate and study the effect of SGR on the roof absorptivity, building temperature, and heat flux. The DesignBuilder simulation tool was used to generate the indoor surface ceiling temperatures and the heat flux for the three zones, zone 1, 2, and 3; for bare and SGRs. These factors are studied to examine the mean monthly data of the three zones. Despite the simulated benefits reaped from DesignBuilder, capable of computationally simulating outdoor relative temperature, the software possesses limitations. Mainly in its inability to simulate the outdoor temperature above the bare and SGRs by 1m. Thus, real-time data was used for comparative analysis. Figure 127 illustrates the indoor surface ceiling temperature reduction from bare to SGRs and the comparable reduction from bare to SGRs for the real-time outdoor temperature at 1m high.

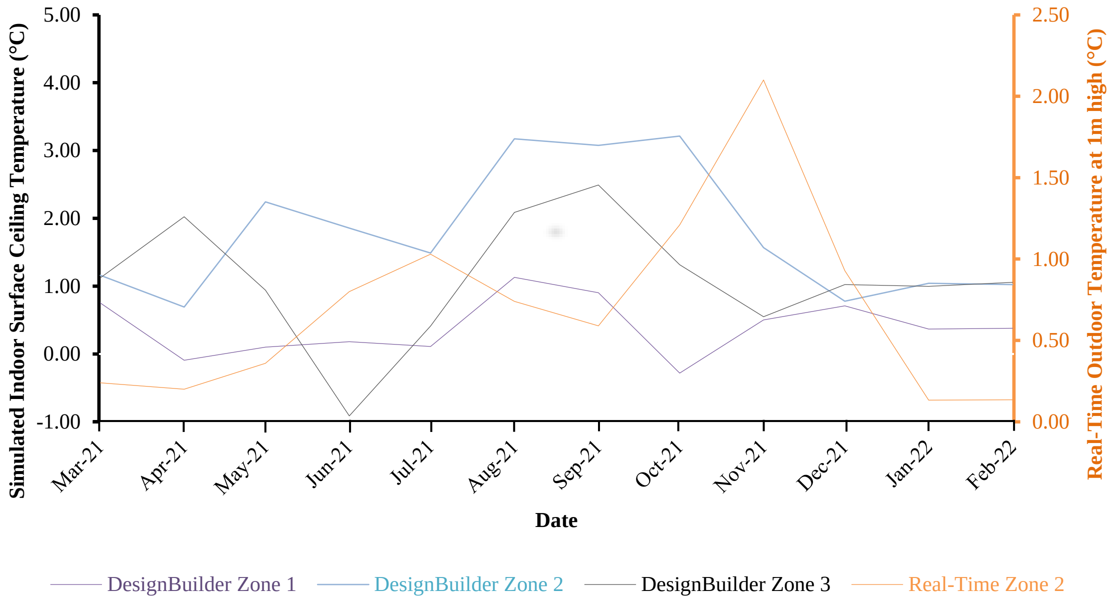


Figure 127. Monthly differences of simulated indoor surface ceiling temperature between bare and smart green roofs for zones 1, 2, and 3; and monthly differences of real-time outdoor temperature at 1m high between zone 2 bare and smart green roofs.

Looking more closely at the differently affected zones of the building, heat flux simulations of the opposing bare and SGRs are distinguished. The introduction of an SGR observantly reduces the amount of heat that is transmitted from the office roof. The heat flux simulated values, with the implementation of an SGR, are inevitably reduced, as depicted by Figure 128.

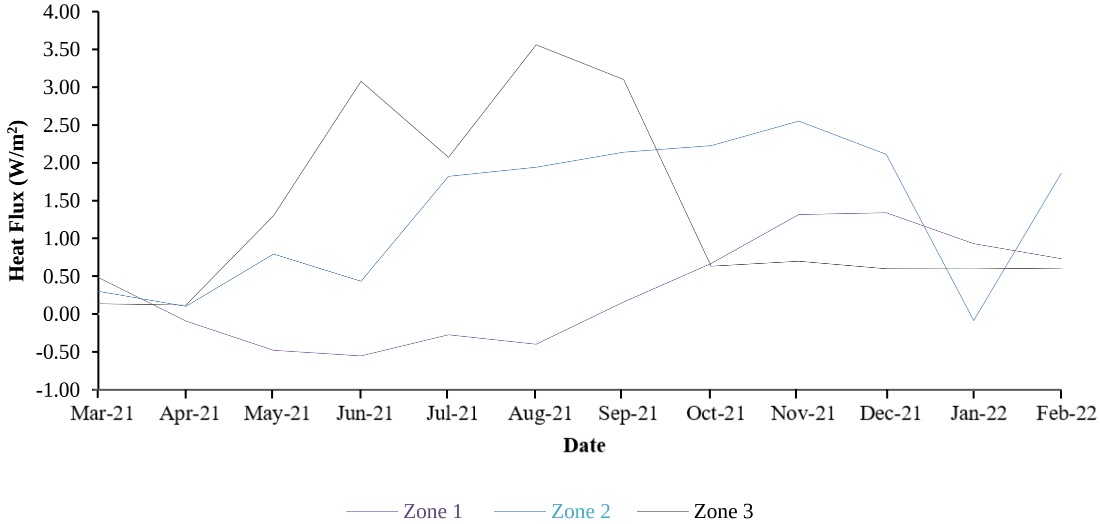


Figure 128. Simulated heat flux of zones 1, 2, and 3: differences between bare and smart green roofs.

Temperature reduction is an important property of an SGR system. The shading and passive cooling effects of plants are effective in temperature reduction. It allows for the reduction of cooling energy consumption. Given the reductions in the indoor surface temperature and heat flux of the building and noting the characteristics of the SGR, it is inevitable for cooling requirements to be lower. Furthermore, shade provided by plants reduces heat gain and cooling loads by diminishing heat transfer through the roof (Wong & Chin, 2018). It has been proven that green roofs increase building energy efficiency by consuming less energy for cooling and heating (Schade et al., 2021). Compared to the bare roof, the cooling energy saving in the office building as a result of SGR implementation will be analyzed. DesignBuilder simulation tool was used to generate the sensible cooling required and calculate the annual energy cost for the three zones: 1 (ground floor), 2 (first floor), and 3 (penthouse), presented in Table 46.

Table 46. Annual energy consumption of the total sum of sensible cooling required and energy cost for zones 1, 2, and 3 bare and smart green roofs

	Sensible Cooling Required			**Annual Energy Cost**		
	Bare Roof (kWh/m^2)	**SGR (kWh/m^2)**	**Bare vs. SGR (kWh/m^2)**	**Bare Roof (QR)**	**SGR (QR)**	**Savings (QR)**
Zone 1	*68.04*	*65.93*	*2.11*	*2883.70*	*2626.12*	*257.58*
Zone 2	*100.20*	*78.18*	*22.02*	*4383.83*	*3203.60*	*1180.23*
Zone 3	*117.63*	*84.32*	*33.31*	*1153.71*	*771.60*	*382.11*
Sum	***285.87***	***228.43***	***57.44***	***8421.24***	***6601.31***	***1819.93***
Annual energy consumption and energy cost saving (%)	**Annual energy consumption = *(annual sum of bare roof – annual sum of SGR) / annual sum of bare roof x 100 = 20.09***			**Annual energy cost saving = *(annual sum of bare roof – annual sum of SGR) / annual sum of bare roof x 100 = 21.61***		

Note. kWh/m^2, kilowatt hour per square meter; SGR, smart green roof; QR, Qatari Riyal; %, percent.

To visualize and assess the extent of the thermal characteristic's impacts on annual cooling loads, Figure 129 has been configured. This is to identify the correlation between the U-Value, R-Value, thermal conductivity, and annual cooling loads of bare and SGRs.

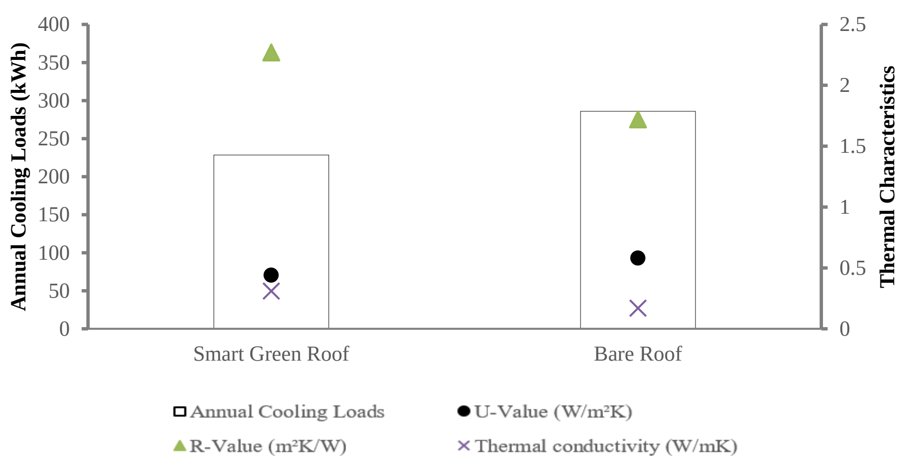


Figure 129. Relationship between annual cooling loads and thermal characteristics (U-Value, R-Value, and thermal conductivity) of bare and smart green roofs.

As presented in this simulation data analysis section, the contribution of new evaluation data and results exemplifies the novel approach to implementing SGRs in Qatar. Conduction of a simulation analysis further validates the beneficial aspects of SGR establishment in hot arid Qatar.

6.3.3.2.1 Statistical analysis between environmental factors and plant performance parameters.

Assessing the simulated LAI against multiple environmental factors, Figures 130, 131, and 132 have been generated. An expected association occurred between LAI and three modelled environmental factors: indoor surface ceiling temperature, heat flux, and outdoor humidity. The figure shows the relationships for the three simulated zones, as the SGR contributes at a different level in each zone.

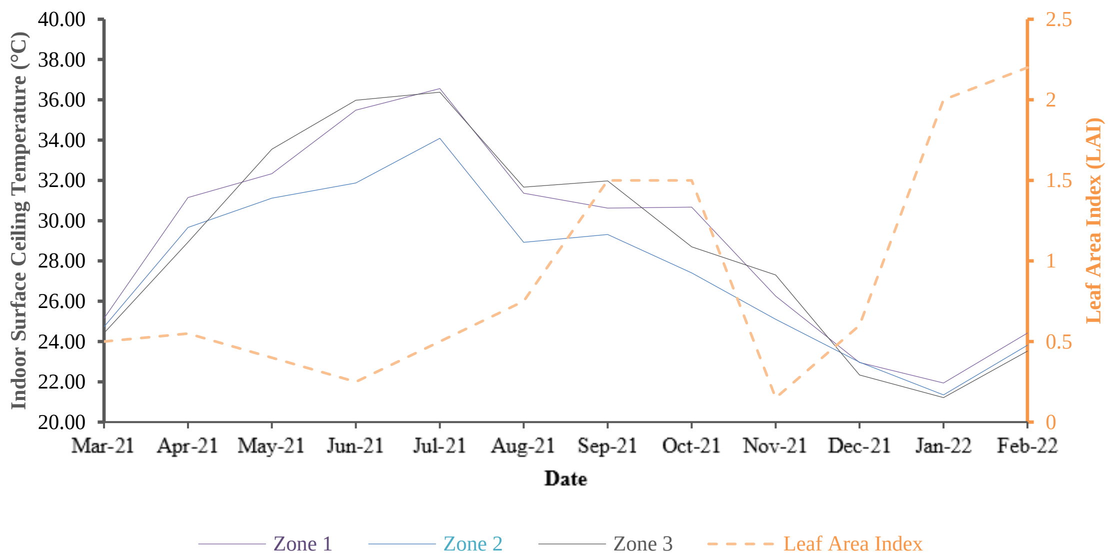


Figure 130. Simulated smart green roof indoor surface ceiling temperature for zones 1, 2, and 3 and LAI.

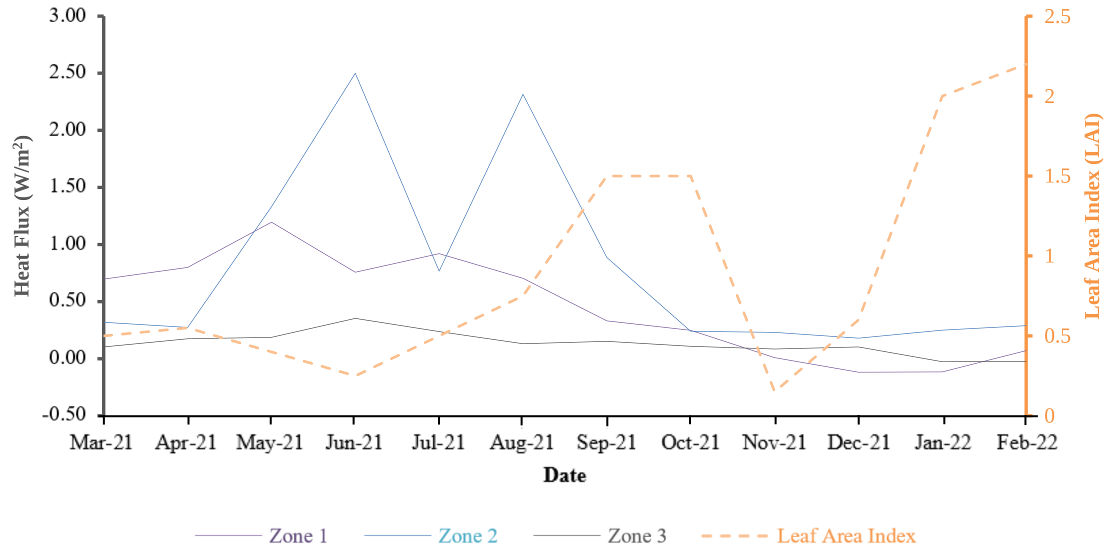


Figure 131. Simulated smart green roof heat flux for zones 1, 2, and 3 and LAI.

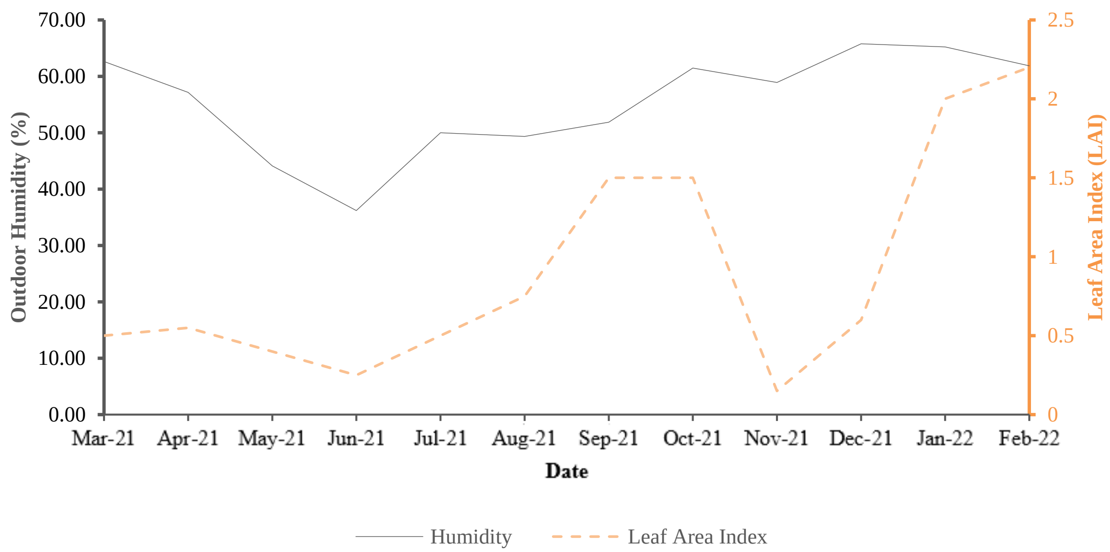


Figure 132. Simulated smart green roof of outdoor humidity and LAI.

Table 47 illustrates the statistical significance between simulated LAI and three studied environmental factors: indoor surface ceiling temperature, heat flux, and outdoor humidity.

Table 47. Statistical significance: *p* values for simulated environmental factors against LAI

Simulated Environmental Factors against Leaf Area Index	***p* value**
Indoor surface ceiling temperature zone 1 and leaf area index	0.15
Indoor surface ceiling temperature zone 2 and leaf area index	0.11
Indoor surface ceiling temperature zone 3 and leaf area index	0.12
Heat flux zone 1 and leaf area index	0.07
Heat flux zone 2 and leaf area index	0.28
Heat flux zone 3 and leaf area index	0.01
Outdoor humidity and leaf area index	0.13

The simulations further responded to a change in another foliage characteristic, the height of plants. While plant canopy is characterized by the LAI parameter with a simulation peak of 2.2, the simulated plant height variations over time directly influence indoor surface ceiling temperature, heat flux, and outdoor humidity, as presented in Figures 133, 134, and 135.

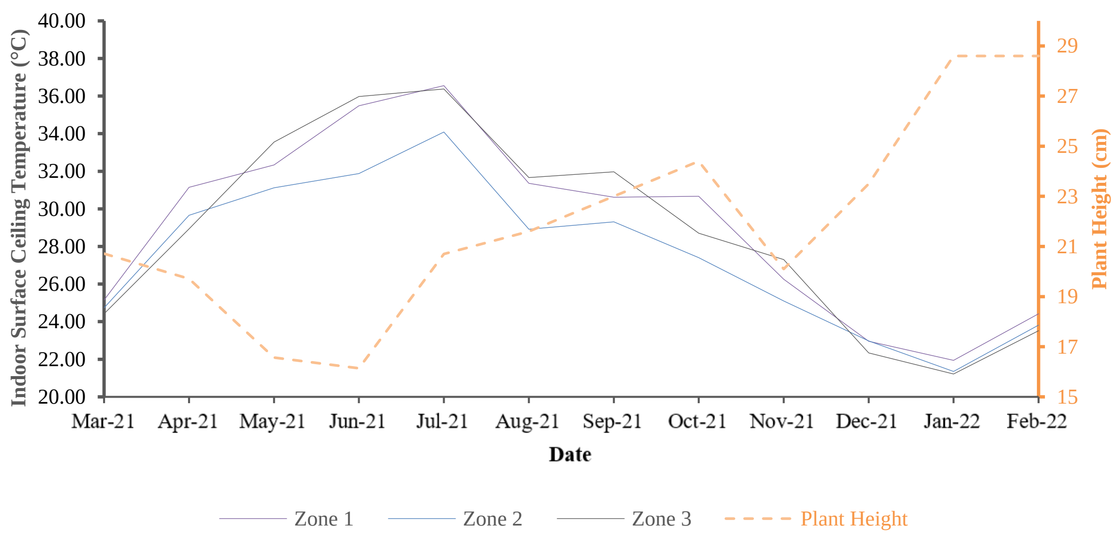


Figure 133. Simulated smart green roof indoor surface ceiling temperature for zones 1, 2, 3 and plant height.

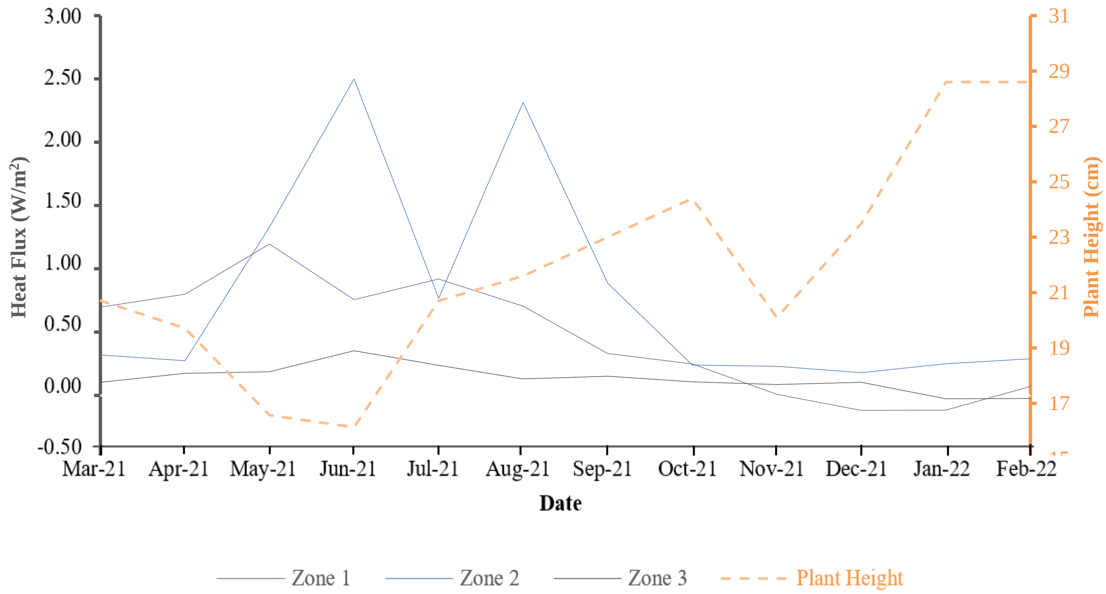


Figure 134. Simulated smart green roof heat flux for zones 1, 2, and 3 and plant height.

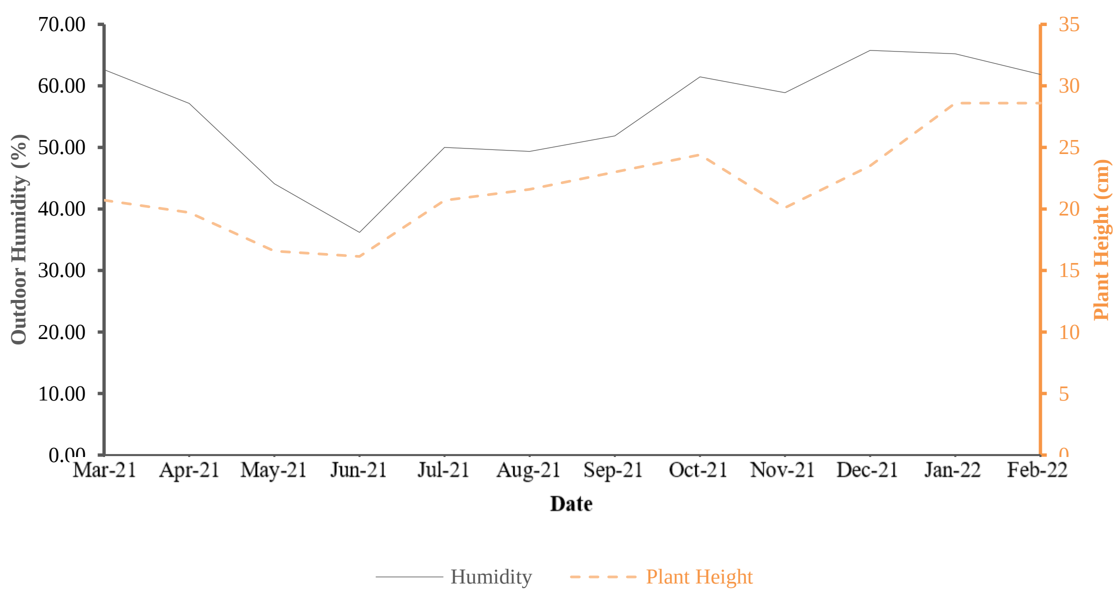


Figure 135. Simulated smart green roof of outdoor humidity and plant height.

Table 48 denotes statistical significance for simulated plant height against environmental factors, indoor surface ceiling temperature and heat flux for all three zones, and outdoor humidity.

Table 48. Statistical significance: *p* values for simulated environmental factors against plant height

Simulated Environmental Factors against Plant Height	***p* value**
Indoor surface ceiling temperature zone 1 and height	0.02
Indoor surface ceiling temperature zone 2 and height	0.01
Indoor surface ceiling temperature zone 3 and height	0.01
Heat flux zone 1 and height	0.00
Heat flux zone 2 and height	0.06
Heat flux zone 3 and height	0.06
Outdoor humidity and height	0.01

For comprehensive insight purposes for this analysis, volume and soil moisture are highlighted. To compare the bare and SGRs with indoor thermal comfort levels, indoor surface ceiling temperature and heat flux were simulated over a year with inputted maximum and minimum soil volumetric moisture content into DesignBuilder. The soil layer initially held 0.15% volumetric moisture content, with saturation reaching 0.45%, with residual moisture content at 0.01%. Table 49 highlights, using the *p* value tool, the statistical significance between simulated environmental factors against plant parameters.

Table 49. Statistical significance: *p* values for simulated environmental factors against real-time plant parameters

Simulated Environmental Factors against Real-time Plant Parameters	*p* value
Indoor surface ceiling temperature zone 1 and volume	0.85
Indoor surface ceiling temperature zone 2 and volume	0.75
Indoor surface ceiling temperature zone 3 and volume	0.84
Indoor surface ceiling temperature zone 1 and soil moisture	0.59
Indoor surface ceiling temperature zone 2 and soil moisture	0.87
Indoor surface ceiling temperature zone 3 and soil moisture	0.08
Heat flux zone 1 and volume	0.29
Heat flux zone 2 and volume	0.47
Heat flux zone 3 and volume	0.68
Heat flux zone 1 and soil moisture	0.33
Heat flux zone 2 and soil moisture	0.24
Heat flux zone 3 and soil moisture	0.87

6.3.3.3 Simulation Peak Day

The July to August 2021 months, representing the hottest period of the year, were then investigated further with simulated data, given its potent temperature and highest heat flux readings. The months were subsequently tested with a targeted focus on one selected peak day, 22 July 2021. Figure 136 depicts the average hourly indoor surface ceiling temperatures of zones 1, 2, and 3 for both bare and SGRs on 22 July 2021. As illustrated in Figure 136, zone 3's (penthouse) bare and SGRs have the highest indoor surface ceiling temperature. Although zone 1 (ground floor) is the furthest away from the roof, it has the second highest indoor surface temperature due to other outdoor factors such as the number of windows, function of floor level, as well as air conditioning. Lastly, zone 2 (first floor) simulated the lowest reading for indoor surface ceiling temperature for both bare and SGRs (Figure 72).

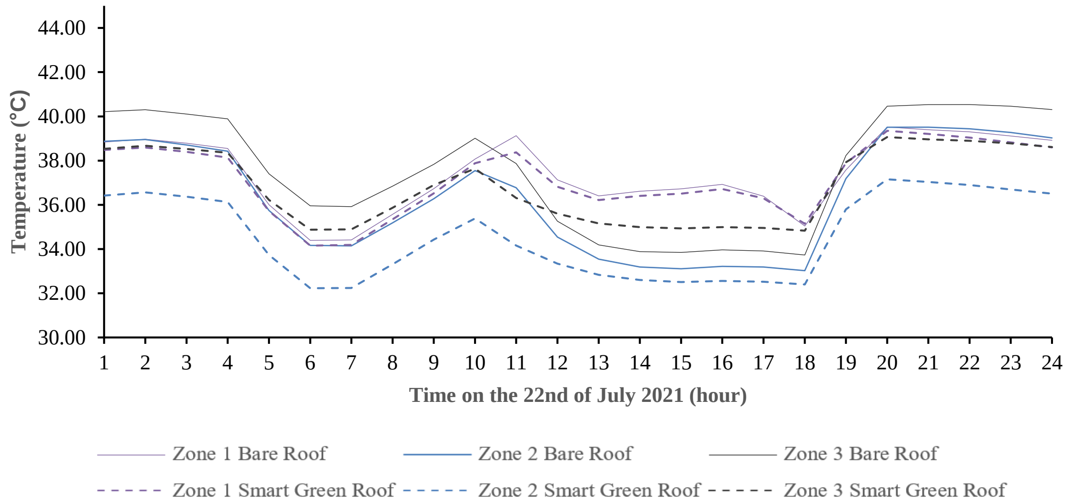


Figure 136. Hourly simulated indoor surface ceiling temperature of zone 1, 2, and 3 bare and smart green roofs on 22 July 2021.

Further real-time data of the average hourly outdoor temperature at 1m high of zone 2 was captured on 22 July 2021 (Figure 137). As demonstrated, in contrast to the bare roof, the SGR reduces the outdoor surface temperature by an average of 1°C throughout the entire day, noting that 22 July ranks as the highest temperature peak of the year.

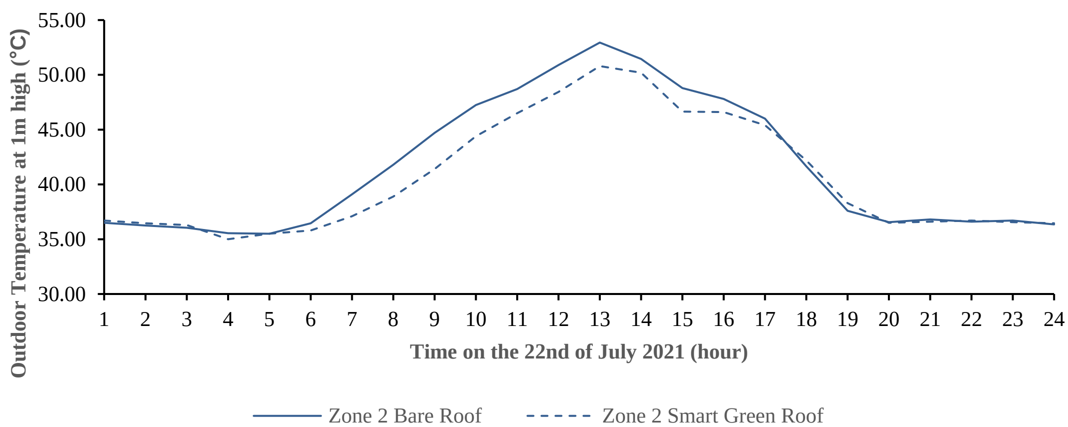


Figure 137. Hourly real-time zone 2 outdoor temperature at 1m high from bare and smart green roofs on 22 July 2021.

Heat fluxes of zones 1, 2, and 3 are exemplified in Figure 138 with a focus on a singular day, 22 July 2021, having experienced the highest heat flux of the study period. It is shown that the zone 2 bare roof has the most increased heat flux, followed by zone 3 bare roof; contrastingly, zone 1 bare roof has the lowest heat flux. To further illustrate SGR's effect on heat flux measurements, it is shown that both zone 2 and zone 3 SGRs present a lower heat flux than zone 2 and zone 3 bare roofs.

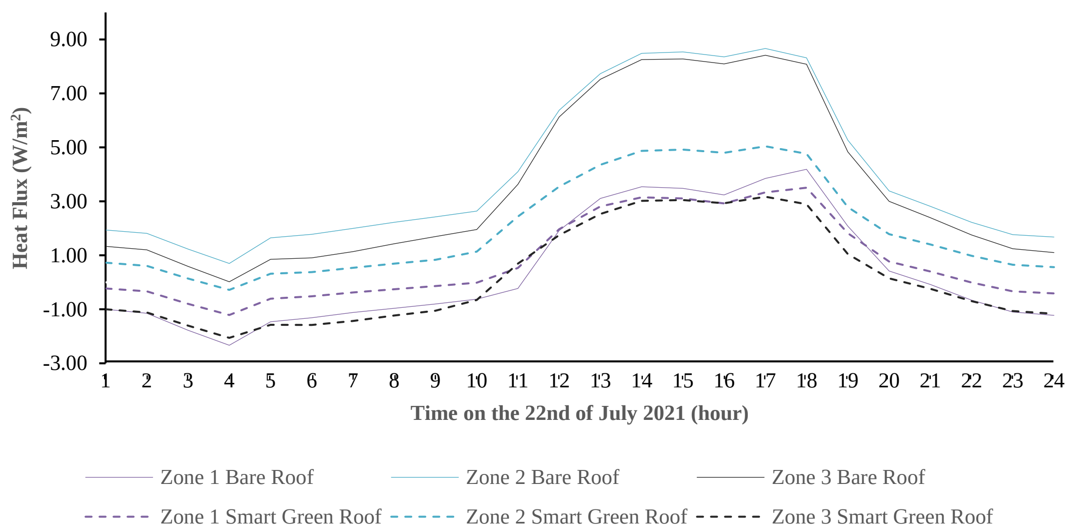


Figure 138. Hourly simulated heat flux showing zone 1, 2, and 3 bare and smart green roofs on 22 July 2021 at summer peak.

The building energy consumption from sensible cooling required on 22 July 2021 for bare and SGRs for zone 1, 2, and 3 during the summer peak is illustrated in Figure 139. Reviewing data readings for bare roofs, it is evident that zone 3 bare roof has the highest sensible cooling, followed by zone 2 bare roof, with zone 1 bare roof showing the lowest sensible cooling curve. It is essential to note that the early hours of the day, from 1 through

4, similarly to the late hours, from 19 through 24, have no energy consumption as DesignBuilder allocated no user occupancy during these hours.

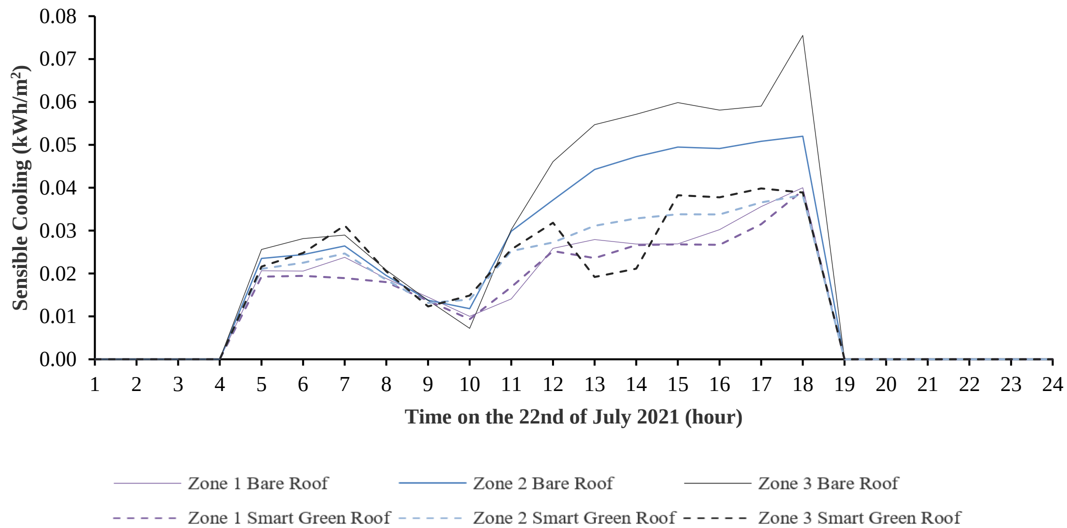


Figure 139. Hourly simulated energy consumption of cooling required on 22 July 2021 for bare and smart green roofs for zone 1, 2, and 3 during the summer peak.

6.3.4 Calibration and Validation

This section provides the analytical data to calibrate and validate the simulated data extracted from DesignBuilder by embedding the weather data file for Doha, Qatar, against the real-time data.

The quality assessment of the building simulation model was based on manual calibration using the mean bias error (MBE), coefficient of variation of the root mean square error CV(RMSE), and coefficient of determination (R2), which are accurate and reliable as statistical calibration standards by ASHRAE Standards 140-2017. According to ASHRAE Standards 140 criteria, for the model to be considered well-calibrated, the values of the evaluation indices should not exceed:

- Daily MBE values within ±7.5% and daily CV(RMSE) values below 22.5%
- Coefficient of determination R2 ≥ 0.75

To assess the accuracy and correlation of the calibration, the simulated data were calibrated for one year, from March 2021 to February 2022. A clear focus on the summer (May 2021 to October 2021) and winter (March 2021 to April 2021 and November 2021 to February 2022) seasons were undertaken, with consideration of the year-round generated data. This calibration employed the use of daily data, depending on the parameter under question. The parametric values of the bare and SGRs data used for the calibration are reported in Figure 140.

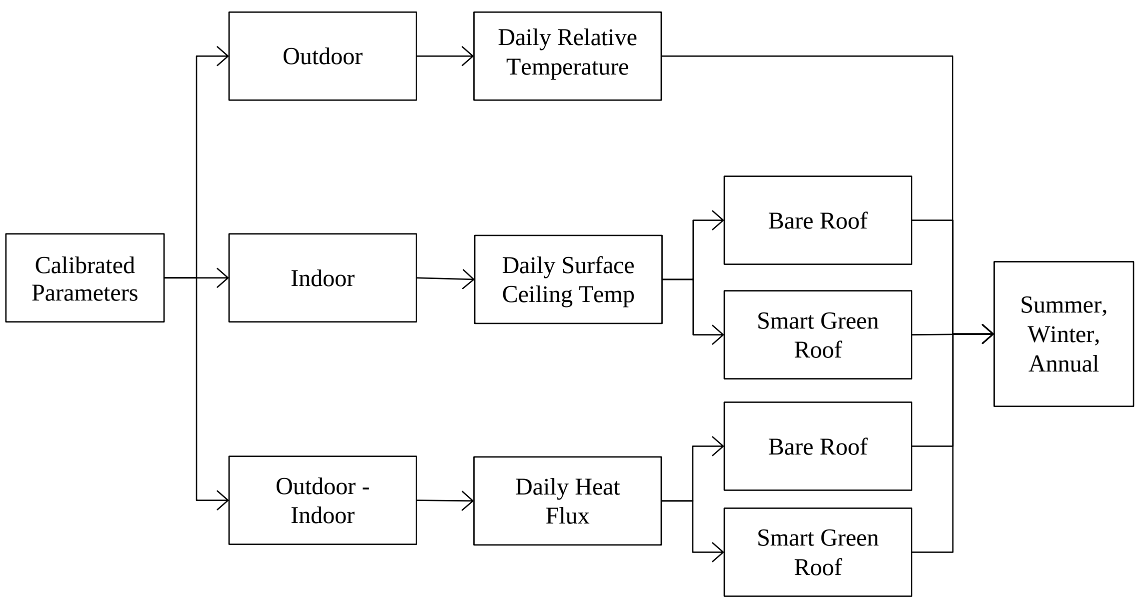


Figure 140. Calibrated parametric values of bare and smart green roofs.

The simulated data have been calibrated against the real-time data, shown in Figures 141, 142, and 143. The data in the calibration process includes daily outdoor relative temperature, daily indoor surface ceiling temperature of bare and SGRs, and heat flux of bare and SGRs.

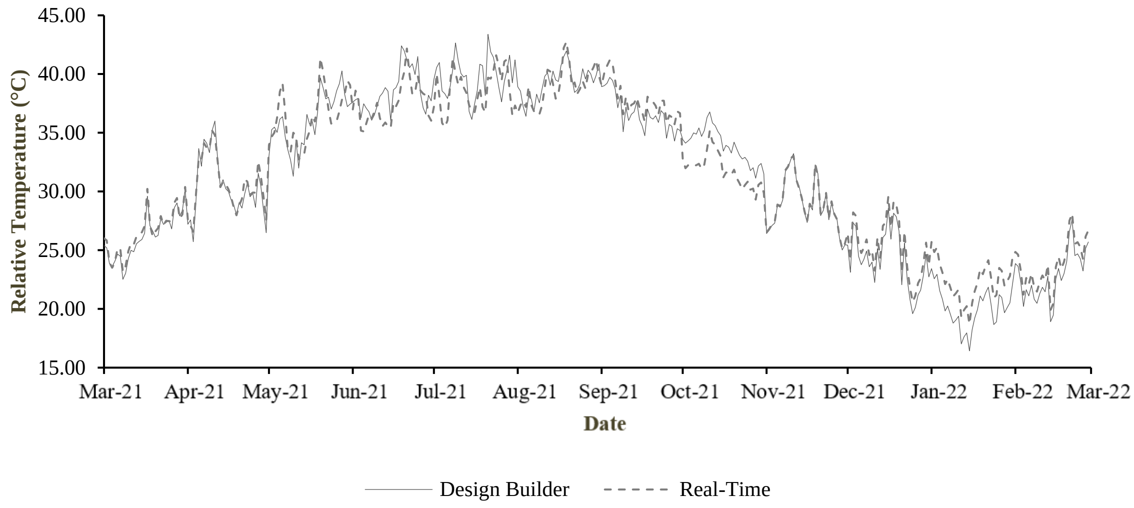


Figure 141. Calibration of daily outdoor relative temperature.

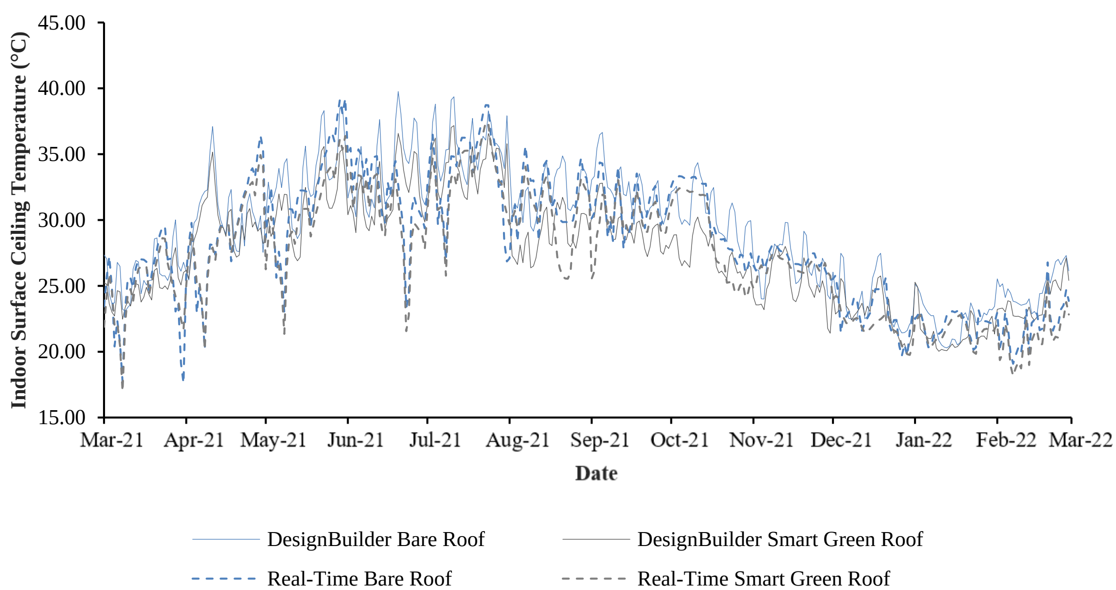


Figure 142. Calibration of the daily first floor (zone 2) indoor surface ceiling temperature of bare and smart green roofs.

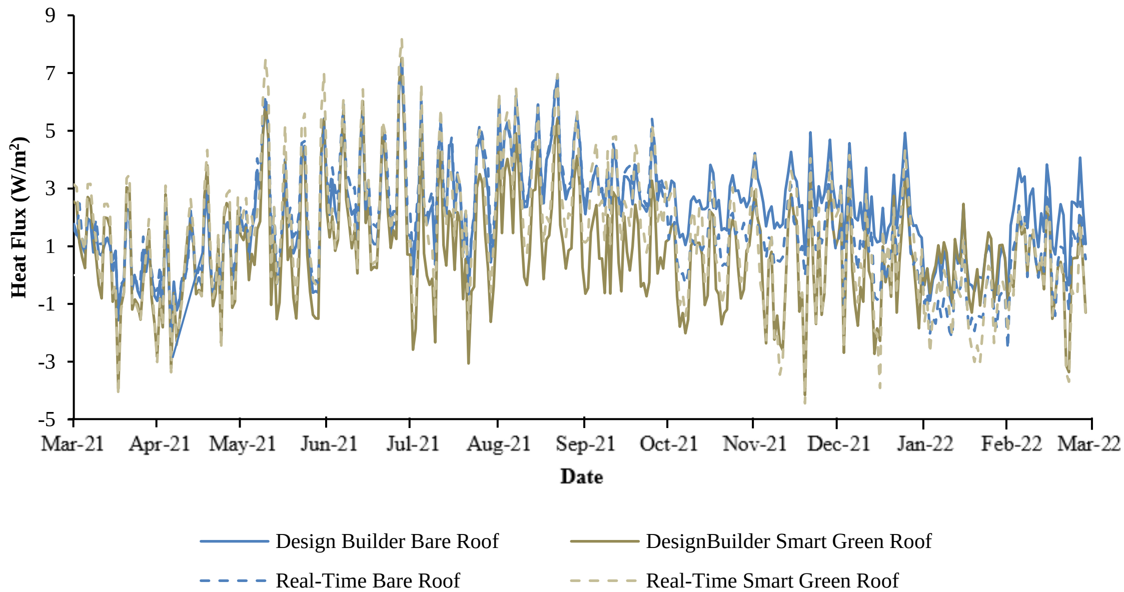


Figure 143. Calibration of daily heat flux of bare and smart green roofs.

Manual calibration was used, and the initial model of DesignBuilder underwent numerous trial-and-error modifications. The setpoint temperature, cooling, heating, lighting, and occupancy values were modified during the calibration. After each simulation run, the MBE and CV(RMSE) values were calculated and compared to the real-time data using the ASHRAE Standards 140 accuracy thresholds. Table 50 summarizes and presents the calibration of the building simulation model. The R2 values show an accurate and reliable correlation between the real-time and simulated data for daily heat flux for the bare roof (79%) and SGR (76%) during the year, daily heat flux for SGRs during the summer (75%), and daily outdoor relative temperature during summer (75%), winter (98%), and the year (96%). There is an accurate correlation between the daily indoor surface ceiling temperature for the bare roof (64%) and SGR (61%) during the year and the daily heat flux for bare during summer (65%) and winter (60%). Moreover, inaccurate and unreliable R2 correlation is shown for daily indoor surface ceiling temperature for the bare roof and SGRs during the summer and winter seasons (17%, 37%, 19%, and 47%), and daily heat flux for SGRs during winter (5%), shown in Table 50. Perhaps this is a limitation in the study where more data was required to eliminate the model's error.

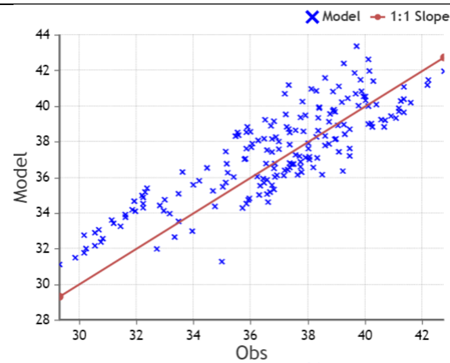
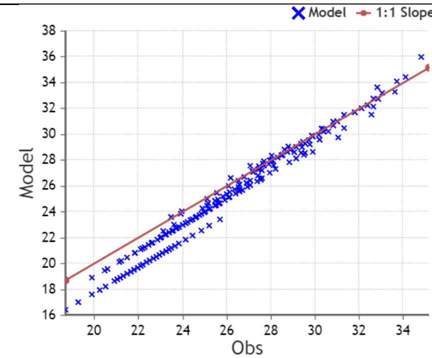
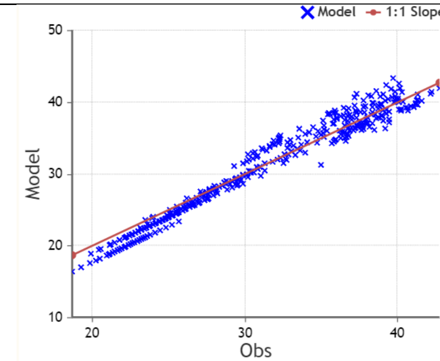
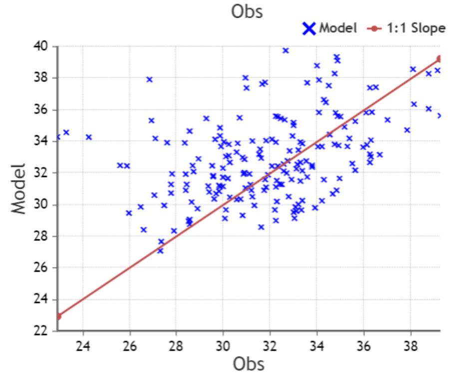
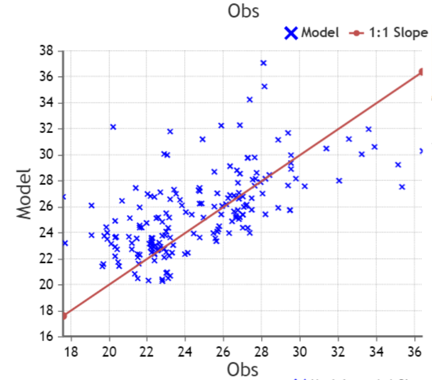
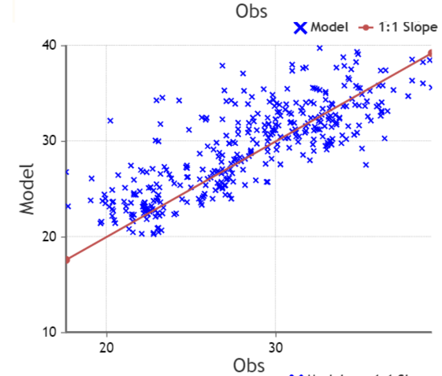
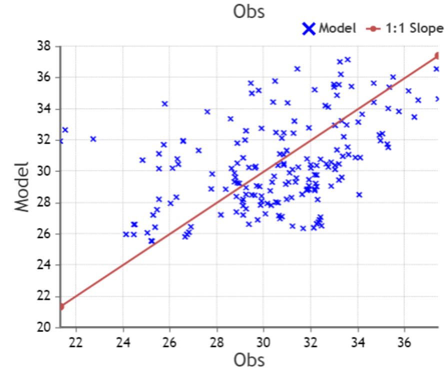
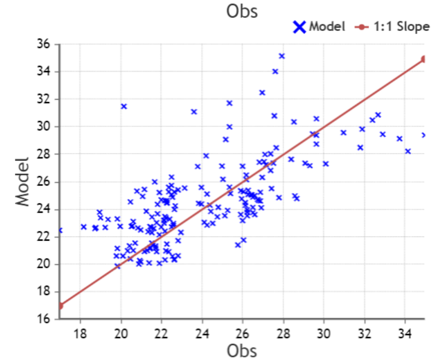
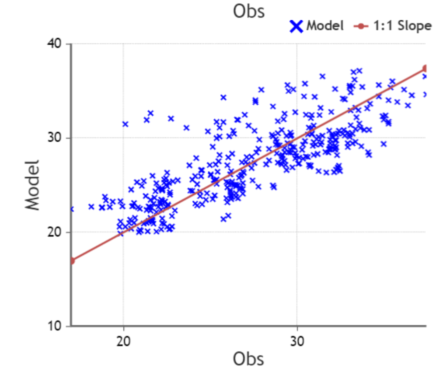
Table 50. Summary of the building simulation model's calibrated parameters

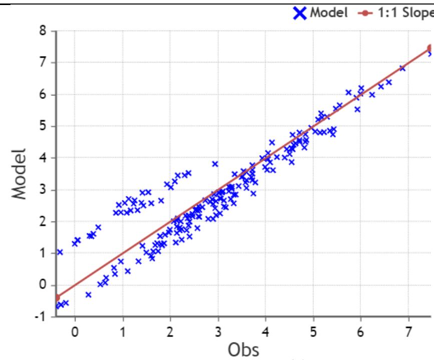
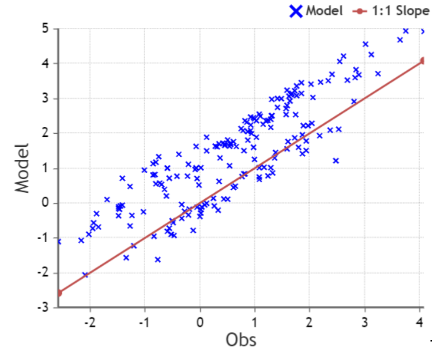
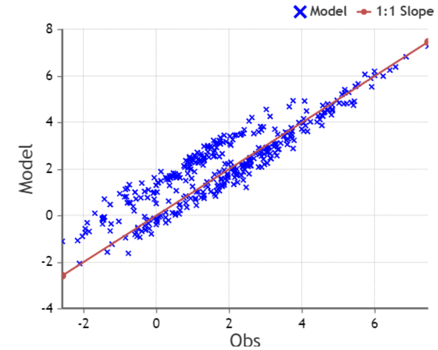
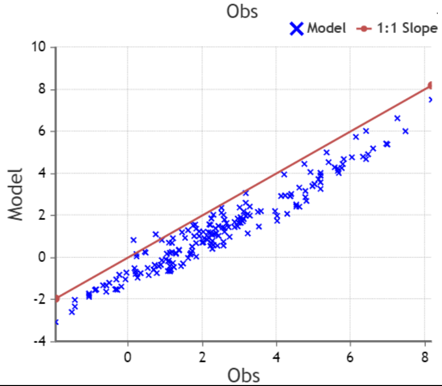
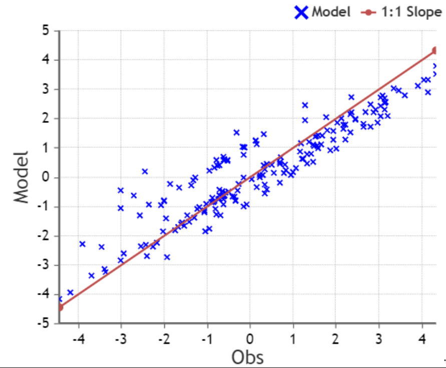
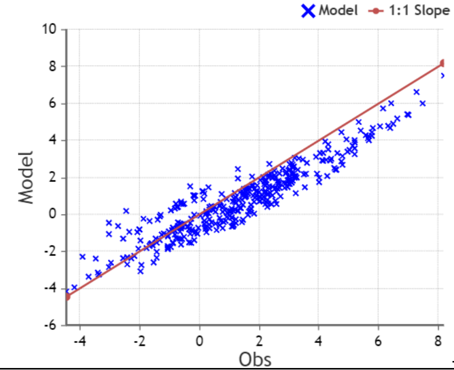
Variables	Calibration Criteria								
	MBE (%)			CV(RMSE) (%)			R2		
	Summer	Winter	Annual	Summer	Winter	Annual	Summer	Winter	Annual
Daily outdoor relative temperature	0.56	-0.82	-0.13	1.66	1.15	1.43	0.75	0.98	0.96
Daily zone 2 indoor surface ceiling temperature for bare roof	1.08	0.94	1.01	3.29	3.08	3.19	0.17	0.37	0.64
Daily zone 2 indoor surface ceiling temperature for SGR	-0.10	0.48	0.19	3.15	2.62	2.90	0.19	0.47	0.61
***Daily* heat flux for bare roof**	-0.04	0.79	0.37	0.60	1.03	0.84	0.65	0.60	0.79
***Daily* heat flux for SGR**	-1.12	0.02	-0.55	1.20	0.63	0.96	0.75	0.05	0.76

Note. MBA, mean bias error; CV(RMSE), coefficient of variation of root square mean error; R2, coefficient of determination; %, percentage; SGR, smart green roof; light grey highlights, indicate accurate and reliable correlation; medium grey highlights, indicate accurate correlation; dark grey highlights, indicate inaccurate and unreliable correlation.

To conclude, it is possible to summarize that using the calibration tools (Table 51), summer, winter, and annual for MBE and CV(RMSE), and annual R2 of the simulated data against the real-time data was considered accurate and reliable to verify the calibration of the DesignBuilder simulation software. Performing calibration of the simulated data against the real-time data allowed the investigation of the potential of an SGR system in reducing the demand for energy in buildings in the studied climate. Thus, data on yearly energy consumption and other variables extracted from the DesignBuilder simulation software can be considered validated and reliable based on the calibrated results.

Table 51. Calibrated parameters from 1 March 2021 to 28 February 2022 with a focus on the summer and winter seasons

Calibrated Parameters	Summer	Winter	Annual
Daily outdoor relative temperature			
Daily zone 2 indoor surface ceiling temperature for bare roof			
Daily zone 2 indoor surface ceiling temperature for SGR			

Calibrated Parameters	Summer	Winter	Annual
Daily heat flux for bare roof			
Daily heat flux for SGR			

Note. SGR, smart green roof; summer, includes May 2021, June 2021, July 2021, August 2021, September 2021, and October 2021 months; winter, includes March 2021, April 2021, November 2021, December 2021, January 2022, and February 2022 months.

6.4 Conclusion

This chapter presents the holistic investigation of SGRs using qualitative and quantitative data. Interview raw responses were acquired to analytically assess the implementation of SGRs in buildings in hot arid Qatar. Peer experts in the field of green roofs provided professional, knowledgeable, and academic opinions on the matters of purpose, difficulty, and enhancement measures with regard to SGR implementation.

Furthermore, the questionnaire was distributed among 170 participants who were frequent users of the space in the three existing office buildings. Contrary to experts' views, they provided unbiased feedback and responses on thermal comfort, air conditioning use, and familiarity with the concept of SGRs in Qatar. This data was quantified despite the qualitative nature of collecting users' thermal comfort.

A combined real-time experimental and simulation approach has effectively measured plant performance. Data measured and generated from this approach allowed for comparing the SGR against the bare roof, with an objective focus on the peak outdoor temperature and heat flux readings. These data measurements and simulations look at the effectiveness of an SGR installation. This is regarding negating the increased building energy consumption elicited by these extreme climatic conditions. Visual observations on general plant conditions, plant arrangement, plant color, and thermal temperature resulted in in-depth coverage of the quantifiable parameters revealing which factors directly influence SGR performance. This is further supported by data on plant growth, smart irrigation system layout and associated dynamics, wind speed, temperature, humidity, and heat flux. For the continuance of the study, necessary adjustments had to be made to podded plant types and arrangement, smart irrigation, and the inclusion of a drainage system.

Analysis of plant performance parameters resulted in in-depth coverage of the SGR components and revealed their subsequent combined effects on indoor and outdoor building and environmental factors. The statistical significance *p* value is an important tool to confirm the relationships between plant performance parameters and environmental factors, specifically indoor temperatures and heat flux. By adopting a significance level of 5%, the findings are likely real, reliable, and not due to chance. It is noteworthy to mention the modelled SGR thermal properties were optimized after multiple manipulations, where the inputted LAI was 2.2, plant height was 28.6cm, and the growth medium thickness layer was optimized at 20cm.

Furthermore, simulated data readings are correlated against real-time data to calibrate the accuracy and reliability of DesignBuilder. The calibration between the real-time and simulated data findings has been established as reasonably close and was satisfactory based on MBE and CV(RMSE) in accordance with ASHRAE Standards. The simulation model is considered calibrated and is assumed fit to be used for further parametric testing.

The collection and analysis of this data greatly expand the current research work in assessing the association between SGR implementation, building energy consumption, and user thermal comfort. Understanding and interpreting these results will help develop design strategies to neutralize the negative effects of Qatar's extreme summer climate on urban environments. Recording plants' performance and monitoring smart irrigation aids in informing the design, development, construction, installation, implementation, and maintenance of resilient and effective SGRs in the hot arid climate of Qatar. These results will be further interpreted in chapter 7 to provide objective benchmarks and key identifiers to improve operating SGRs.

PART 2 CONCLUSION

This part of the dissertation is concerned with contextualizing the methodological approach to understand the data acquisition and analysis process. Identifying the research problem as one that deals with environmental concerns in the hot arid region of Qatar facilitates the derivation of the focused aim of the research. By first designing a smart green roof system, the concurrent development and implementation of an SGR will enable the formulation of design recommendations. Upon such a research stance accompanied by the definition of a combined research method, the use-case becomes appropriately justified through qualitative and quantitative means.

Shaping the experiment around existing Qatar meteorological data, the constituents of the setup fall into place seamlessly. A representative office low-rise building is selected to carry out the study. Further delineation of SGR model materials data for simulation purposes portrays plant and thermal properties. The SGR is situated in a modular pod system inclusive of a vigoroot geotextile wicking material, growing medium at 20cm, and stress-tolerant and low-, self- growing plants, with a smart irrigation system in place.

Data is acquired through qualitative means, recording the indoor environment quality and thermal comfort of 170 office users'. These data are analyzed to observe trends and patterns of user experience regarding room perception, comfort conditions, adaptive strategies employed to accommodate their environment, and familiarity with SGRs. The interview, on the other hand, was conducted to assess the knowledge and awareness of professionals in the field regards SGRs.

Another aspect of data acquisition lies in quantitative means. This was two-fold, a segment of real-time data alongside computer-generated simulation data. Real-time data captured plant performance in terms of color and growth. With necessary adjustments to the SGR system, a foundation to improve plant conditions was laid. Having begun with manual irrigation, sustainable drip irrigation and incorporating a drainage system soon followed, with data proving enhanced plant conditions due to the smart irrigation system. An effective, well-performing SGR is the basis for measuring environmental factors and building energy consumption. Measurements of wind speed, temperature, humidity, and heat flux were collated. To note, a reduction of the indoor heat flux and temperature as a result of the introduction of the SGR system was observed, enhancing the users' comfort within the building.

As for the latter, the same environment parameters were simulated in similar use-case study conditions. With simulation software, a closer look into the statistical analysis between environmental factors and plant performance parameters was effectively made. Heat flux was associated with LAI and plant height, as particularly noted for zone 3. However, a stronger association, indicated by the *p* value, was between indoor surface ceiling temperature and plant height for all zones. Based on the simulated data, a notably low energy consumption of cooling was characterized in the SGR as opposed to the bare roof. Furthermore, the correlation between the thermal characteristics and annual cooling loads of bare and SGRs have been configured. Finally, the simulated data against the real-time data was considered accurate and reliable to validate the calibration of the DesignBuilder simulation software.

Naturally flowing in the progression towards an interpretation of the analyzed data, a summary of the research findings is stipulated, followed by conclusive remarks and future directions for design recommendations in the final part of the dissertation.

PART 3: RESULTS INTERPRETATION, CONCLUSION, AND FUTURE DIRECTIONS

PART 3 INTRODUCTION

The evolution of green roofs over many years is paramount to this research study. This final part of the thesis signifies a milestone, as it interprets the results of the smart green roof (SGR) use-case and highlights significant findings to address the research question. Individual interpretations of qualitative and quantitative results are made, followed by a cohesive interpretation conclusion incorporating qualitative, quantitative, and simulated result findings.

The thesis is concluded with conclusive remarks and SGR design recommendations for potential use by the government, decision-makers, architects, and urban planners. It also elaborates on study limitations and suggests future research study directions (Figure 144).

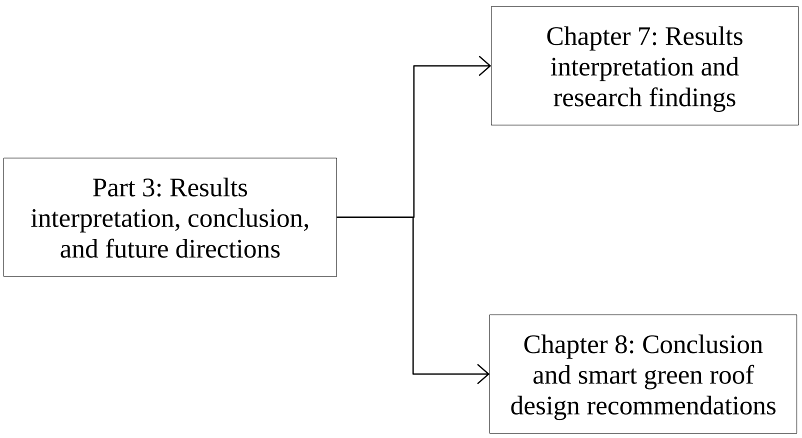


Figure 144. Part 3 results interpretation, conclusion, and future directions.

CHAPTER 7: RESULTS INTERPRETATION AND RESEARCH FINDINGS

7.1 Introduction

The previous chapter displayed differences between bare and smart green roof (SGR) properties and influences on visual plant and quantitative parameters. This chapter links to the previous chapter and aims to identify the impact of placing an SGR system in a hot arid urban setting through interpretation.

The questionnaire and interview responses aid in understanding the realistic societal norms of SGR implementation. While illustrating plant performance and its effects on the building will address the investigative and assessment research objective of the user thermal comfort as an adjunct to building thermal properties. The application of a smart irrigation system is discussed, along with the impact of the SGR on building roof absorptivity, thermal performance, and energy consumption.

7.2 Qualitative Results Interpretation

Experts are an important source of information that provides valuable qualitative input into the internal space of a building. To annotate the perceived knowledge on SGR use, interview-style responses were aggregated to grasp experts' opinions. Jointly, quantified questionnaire responses and qualitative interview data provide a holistic viewpoint of the complexity of SGRs as a representative causal component to the building environmental conditions.

During summer, the days are longer with longer sun exposure. As a result of the building structure, the sun's heat energy falls directly on the higher floor levels, causing the first floor to be hotter than the ground floor. Thus, it is vital to note that operating mechanical cooling devices to offset the increased heat build-up increases building energy consumption.

The experts' familiarity and knowledge of green roofs, there remained a gap between research and implementation. Thus, by showing the need to mitigate the heated building and higher temperatures resulting from a hot arid climate, the findings of this study should be exploited for potential SGR design and implementation.

Interviewed experts expressed many positive outcomes resulting from SGR application, noting that an appropriate type and structure must be constructed to achieve results of any nature. There were conflicting opinions on its ability to reduce noise (60% of experts disagreed), to improve public health (27% of experts disagreed), and to reduce ambient temperature (13% of experts disagreed); it should be noted that no one system has the ability to facilitate beneficial effects. This deficiency might be correlated with improper installation, lack of maintenance, financial liquidity, cultural and societal practices, and governmental legislation, among other facets.

To further illustrate experts' disposition on SGR applicability in hot arid Qatar, a perceptive aesthetically pleasing rooftop greenery resulting from the inclusion of nature was conveyed. However, the placement of what naturally belongs on the Earth's ground to an urban building's vacantly bare flat rooftop is a juxtaposition that gives rise to two major concerns, water accessibility, and building structural integrity.

This study aims to design, develop, and implement SGRs to prove their efficiency in reducing building energy consumption and enhancing user thermal comfort. It does so by outlining a set of design recommendations to develop and implement an SGR capable of withstanding and persevering in the hot arid climate of Qatar. Only by acquiring the correct information can field experts comprehend the benefits, fallbacks, and limitations associated with SGRs. The qualitative interview data uncovered the need for an intervention to enhance building functionality, thus implementing an SGR system.

7.3 Quantitative Results Interpretation

An interpretation pertaining to quantitative data is covered in this section. Questionnaire results are quantified to assess the degree of and ultimately halt user discomfort. With regards to real-time data stemming from visually observed data, quantified information on the plant's general condition (arrangement, color, growth, and thermal temperature) and smart irrigation corroborate the findings of environmental measurements: wind speed, temperature, humidity, and heat flux. Further, properties that measure thermal and heat characteristics of building material will be assessed, including sensible cooling and energy consumption, U-Value, R-Value, and thermal conductivity. Further supporting this, simulated data focusing on a peak day is interpreted.

7.3.1 Questionnaire Results Interpretation

Indoor environmental quality (IEQ) in an office building without an SGR adversely affects its users' performance, health, and well-being. Considering Qatar’s climatic conditions, a questionnaire captures the influence of environmental conditions on building users’ satisfaction and thermal comfort level.

Considering that most of the employed users worked on the first floor, a relatively large percentage accounted for a decrease in IEQ due to summer weather conditions. Credibly, PMV in winter months registered at -1, while in summer, PMV indexed at +3, indicating the trapped heat in the office building interior. The summer PMV is not within the acceptable ranges of the ISO 7730 criteria for existing buildings (Guenther, 2021). Thus, design considerations and interventions must be considered to enhance the users’ thermal comfort sensation within the building.

In addition, data findings indicate that a metabolic rate is influenced by various parameters which work concurrently to offset thermal discomfort in the building. Further intensifying the association between thermal discomfort and diminished overall health resulted from decreased physical activity and increased drink uptake.

Furthermore, study results have shown that the clothing insulation of users is directly affected by temperature. An observed 0.3 clo reduction in clothing insulation value is evident in temperatures above 30°C in the summer compared to a comfortable temperature of 23°C in winter. This data illustrates thermal comfort's impact on users' adaptive strategies to warmer indoors.

Moreover, it is found that the three office buildings do not offer the users with optimal thermal comfort. In order to maintain a reasonable indoor temperature during winter and summer, users must utilize active cooling and heating systems in the office, which is indicative of poor building design in terms of climatic conditions, sustainability dimensions, and material selection. The building is also greatly affected by outdoor environment conditions, as the increase or decrease of outdoor temperature directly impacts the comfort level of users' inside the office building. This occurs due to a lack of thermal mass, poor insulation, inappropriate building design, air leakages, and other factors.

Thus, SGR implementation must be validated to manipulate indoor building temperature, thus affecting a user's thermal experience. This dissertation will provide merit to SGRs in Qatar's hot arid climate, providing a reference point to contextualize SGRs implementation. The research findings presented an outlook of user dissatisfaction with hot indoor environments resulting from interactions between outdoor climate conditions and the building's design.

7.3.2 Real-Time Results Interpretation

Contrasting values of the winter and summer means are evident in plant color; expectedly, lower plant color values were registered in the hotter months, with better color values quantified in the cooler winter months (Table 39). Considering height and LAI simultaneously, as they are both measures of plant growth, a two-fold and ten-fold increase occurred, respectively, from the minimum to maximum values. This exemplifies the effective maintenance of SGR plants. This is further supported by the addition of fertilizers on 12 June 2021, in which nitrogen acted to increase the growth of leaves, phosphorous encouraged strong and healthy root growth, and potassium aided the growth of flowers (Razaq et al., 2017). Denser plant foliage indicates high LAI and plant maturation (deeper color), reducing solar radiation received by the building envelope and absorbing more sunlight energy (Wong & Chin, 2018).

The denser the leaf coverage of plants, the higher the LAI of the SGR; the opposite also applies. LAI is variable due to the plant canopy, foliage density, plant leaf size, and plant maturity. The higher the LAI measurement, an improved plant condition ensues. This is because a higher LAI results in solar radiation reflected by plant leaves, decreasing the total radiation transmitted to the building envelope.

An element analyzed for the water demand reduction strategy was the study of soil conditions based on its moisture level (Table 39). The irrigation solution reached the optimal soil moisture level varying from 40-45% depending on the climatic weather condition by smartly and sustainably dimensioning the water supply to the intended use. More specifically, during summer months, the soil sensor trigger will be set to a higher irrigation of 45%, while in winter months with cooler climate conditions, the plants will require comparably less water; thus, the irrigation trigger is to be set at 40%.

It was decided this was optimal because soil moisture levels indicated as such, as the soil moisture sensor efficiently cuts the irrigation time at the specified trigger level. Furthermore, at a set 40% smart irrigation trigger, only evaporation was observed, with no indication of run-off. At a prior 60% trigger, the experimental program slightly overwatered, meaning that some water was going to waste. Thus, a safe decrease in the trigger level to 40-45% meant no harm or negative effects befell the plants.

The mean soil moisture throughout the winter and summer remains relatively high and consistent (Table 39). With a small standard deviation, 46.98 (4.72), variability in soil moisture data is minor, denoting that the soil held similar water content among all months of the year, regardless of whether during the winter or summer season. Accordingly, the ability of the soil to retain water provides the means to distribute water for plant growth (Atefeh, 2017).

IRRIOT allowed for reducing the risk of overwatering because a precision soil moisture sensor was connected to irrigation logic. It is known from practice that most plants enjoy a water level of between 20 and 50% (Singer & Munns, 2006). Of course, when photosynthesis slows down in cooler times, the water demand is lower. Having excess water in the potted plant substrate flushes away nutrients, effectively depleting the soil, may cause root disease, and is synonymous with wasting the water resource.

IRRIOT sets so-called irrigation conditions that automatically maintain the soil moisture within the specified range. The system user does not determine the frequency and amount of water, as it is automated by integrating the soil moisture sensor. In addition to the automation of water dispensing, it is important to monitor, by visual control, the wellness of the plants. Hence, necessary adjustments were made to the experimental research based on ocular inspection.

The analysis also proved that soil temperature depends on soil moisture level, demonstrating the interaction of soil temperature and soil water availability. The land has a higher tendency than water to absorb and retain more heat, while the water reflects solar radiation rather than trapping it (Berkeley, 2022). Compared to summer data, higher mean soil moisture in winter corresponds with lower soil temperature, denoting the conceptual strength of the specific heat capacity of the water available in the soil (Table 39).

A higher mean soil temperature in summer compared to a low mean in winter is correlated negatively with vegetation abundance and richness (Table 39). The results indicate that weather conditions directly impact color, height, and LAI plant parameters, indicating that the plant cannot withstand the heat trapped by the soil. With a higher mean soil temperature in summer than winter, 33.83ºC, lower data points for color, height, LAI, and soil moisture were registered, 3.02, 20.40cm, 0.82, and 46.46%, respectively. The relationship between soil temperature and the abundance of vegetation is significant, distinguishing that the condition of soil temperature can affect plant growth (Atefeh, 2017). Many of the selected native plant species are thus examined to tolerate extreme heat temperatures and adequate water supply (Armada et al., 2016; Marchin et al., 2022; Williams et al., 2010).

Furthermore, the relationship between soil temperature, soil moisture, plant foliage, and vegetation parameters are synergistic. Plant growth requires water, hence the benefit of having a reasonable soil moisture level. The result of this study indicates that photosynthesis and leaf growth is stunted by water stress; concurrently, warmer soil negatively affects vegetation performance. The opposite also applies; vegetation cover reduces soil temperature as the leaves reflect the heat before the solar radiation arrives (Sinclair et al., 1973).

Manual irrigation corresponds to the months grouped under 'mean winter 1', while smart irrigation lays over the months under 'mean summer' and 'mean winter 2' (Table 39). The mean volume of water consumed by plants during manual irrigation is significantly proportionately higher than during smart irrigation. It can be interpreted that smart irrigation ensures a sustainable and reliable system saving water consumption by a little over 100-fold. The mean winter 2 volume, 10.28L, is also considerably very close to the minimum water volume consumed over the entire year span, 8.96L. Reducing excess water use improves the health of the soil and hence the plants (Kukal et al., 2014; Shrivastava & Kumar, 2015). Therefore, smart irrigation is an optimal system for an extensive green roof. It is proven that using a smart irrigation system assists in tracking and thereby sustaining the plants' water demands.

The selected real-time experimental enclosed room was occupied. During the experiment, it was ensured that the room used for measuring the thermal properties of the internal spaces coinciding with the roof was continuously air-conditioned with the thermostat set point temperature at 22°C. Thereby, the air conditioning system remained on during occupied and un-occupied hours. Windows were also permanently closed during experimentation to ensure a controlled environment.

Observing the values for the relative temperature to be lower in winter than in summer is natural. Explicitly, due to the course of the experiment, and with the lasting effects of the presence of the SGR, the winter two months recorded a mean of 25.09ºC, markedly lower than that of the winter one month, with a mean of 28.58ºC (Table 40). This is likely related to changes in the vegetative cover on the SGR, with higher height and LAI values detected in the winter two months, 25.2cm and 1.24, respectively, as opposed to 20.21cm height and 0.53 LAI in averaged winter one month.

It is evident that temperature and humidity levels with SGR implementation, whether indoor or outdoor, are lower than those without green roof plants. Soil temperature may be associated with the relative temperature. In the instance of maximum recorded values, the peak soil temperature was recorded at 38ºC compared to 42.75 ºC maximum relative temperature (Table 40). Therefore, it is understood that the plants absorbing the heat will transfer less into the building envelope. Improved cooling performance due to the soil temperature plant parameter is a feature of vegetated roofs (Wong & Chin, 2018). These results are in agreement with the research objectives.

Regarding wind speed, the green roof seemed to have no direct influence on this factor. Stronger wind speed occurred in winter months, 4.48m/s, compared to a mean of 3.68m/s wind speeds in summer months. Table 40 also shows that SGRs have a smaller effect on wind speed than their higher impact on humidity, temperature, and heat flux factors. Therefore, the changes in wind speed over the months of the real-time experiment are not substantial in office areas.

Congruently, there was an improvement in outdoor and indoor humidity, outdoor temperature readings at 1m height from the roofs, indoor surface ceiling temperature, and heat flux. These factors experienced a considerable drop as a consequence of the efficiency of SGRs (Table 41). The difference in humidity levels between outdoor and indoor levels was much greater at the beginning of the experiment. Toward the end of the experiment, the humidity levels between the outdoor and indoor areas of the implemented SGR dropped and were consistently similar (Table 52). However, it is critical to note that the bare roof effectively reached a lower minimum outdoor humidity over the year-long experimental timespan, a value of 8.48% over a 9.59% outdoor humidity reading as a result of SGR application. This occurrence is as would be expected, as plants increase humidity in the air as a result of the evapotranspiration process. This, however, should not deter the effects the SGR has on the indoor humidity experienced in the building by the user. Outdoor humidity also showed the highest variability reduction from the controlled bare roof to the SGR, meaning that the standard deviation from the mean shifted from 14.03% to 13.45% from bare to SGR. Thus, fewer fluctuations in outdoor humidity occurred over the experimental phase when the SGR was effective.

Table 52. Difference between outdoor and indoor humidity for bare and SGRs

	Humidity (%)											
	Mar-21	**Apr-21**	**May-21**	**Jun-21**	**Jul-21**	**Aug-21**	**Sep-21**	**Oct-21**	**Nov-21**	**Dec-21**	**Jan-22**	**Feb-22**
Bare Roof	30.55	20.00	3.82	-5.34	-2.24	-1.68	-1.93	8.31	3.05	6.01	6.12	4.62
SGR	30.25	21.20	7.13	-0.99	2.25	-1.27	-0.23	6.23	2.57	3.97	8.51	3.15

Note. SGR, smart green roof.

As opposed to the lo wer standard deviation in outdoor humidity, indoor humidity conveyed a reverse in the variability of values from the mean when considering the bare roof to the SGR. Correspondingly, a rise in standard deviation from 11.13% to 11.51% was observed; thus, the SGR incurred a higher variability from the mean in indoor humidity throughout the year (Table 41). This highlights that perhaps other uncontrolled factors outside this experiment's scope might have led to a higher variability, despite reaching lower mean summer and mean winter indoor humidity levels, 46.33% SGR against 48.34% bare roof, and 44.17% SGR against 47.94% bare roof, respectively.

As for the outdoor temperature at 1m height, the SGR effectively decreased the mean readings by more than double in winter than in summer (Figure 145). The sensors picked up a 0.79ºC drop between bare and SGR in mean summer, with a recorded 1.83ºC reduction in mean winter pertaining to the application of the SGR. This falls in line with the research objectives, exerting an agreement to the benefits outweighing the disadvantages.

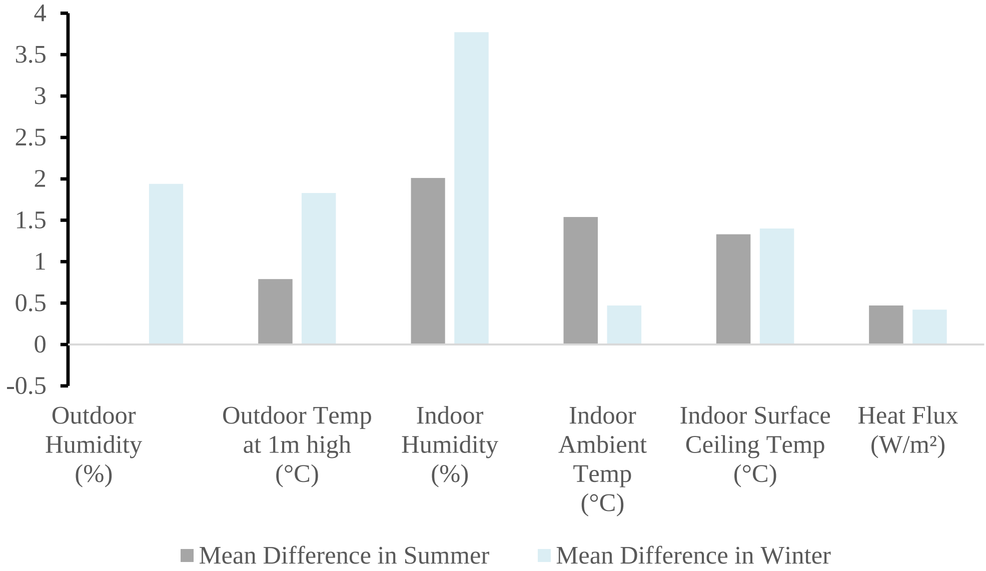


Figure 145. Mean differences of real-time zone 2 bare roof vs. smart green roof in summer and winter.

Note. Temp, temperature; m, meter; °C, degrees Celsius; %, percent; W/m^2, watts per square meter; mean difference in summer, includes May 2021, June 2021, July 2021, August 2021, September 2021, and October 2021 months; mean difference in winter, includes March 2021, April 2021, November 2021, December 2021, January 2022, and February 2022 months.

The SGR efficiently decreased the maximum and minimum results for outdoor humidity, outdoor temperature at 1m height, indoor humidity, indoor surface ceiling temperature, and heat flux. Despite reaching a lower maximum value, the SGR implementation could not achieve a lower minimum in the indoor ambient temperature. The zone 2 real-time SGR illustrated an 18.61ºC minimum indoor ambient temperature. At the same time, the counterpart bare roof was more effective in affecting a lower minimum indoor ambient temperature by an entire degree with a 17.44ºC result throughout the year-long experiment (Table 41).

There was a reduction in the indoor surface ceiling temperature and an observed reduction in heat flux (Table 41). The SGR showed that plant performance parameters have a great deal of influence over environmental factors. The importance of greenery to urban office buildings, through the selective design, development, and implementation of an SGR, is paramount to a sustainable and contactless environment. Figure 145 shows the differences between bare and SGRs for the mean summer and mean winter values.

The denser the leaf coverage of plants, the higher the leaf area index (LAI); the opposite also applies. LAI is variable as a result of the plant canopy, foliage density, plant leaf size, and maturity of the plant. The higher the LAI measurement, the better the plant condition. This is because a higher LAI causes solar radiation to be absorbed by plants, decreasing the total radiation transmitted through a building (Wong & Chin, 2018). Increasing the surface reflection of solar radiation with plant cover allows controlling the building's solar radiation and indoor surface ceiling temperature. It was evident that the effectiveness of the SGR's ability to reflect solar radiation was dependent on the LAI and percentage of green space coverage, along with the substrate of the plants. It is also worth noting that most plants selected had many smaller leaves, which are more effective than the few large leaves; the size and shape of leaves are also a factor in determining the heat dissipation rate (Perini, Ottelé, Fraaij, Haas, & Raiteri, 2011). Therefore, by effectively reflecting solar radiation, the SGR was able to decrease the temperature entering the building envelope efficiently; hence lower indoor surface ceiling temperatures were achieved. As illustrated by Figure 146, only a 10% chance of a statistically significant relationship between indoor surface ceiling temperature and LAI might have occurred by random.

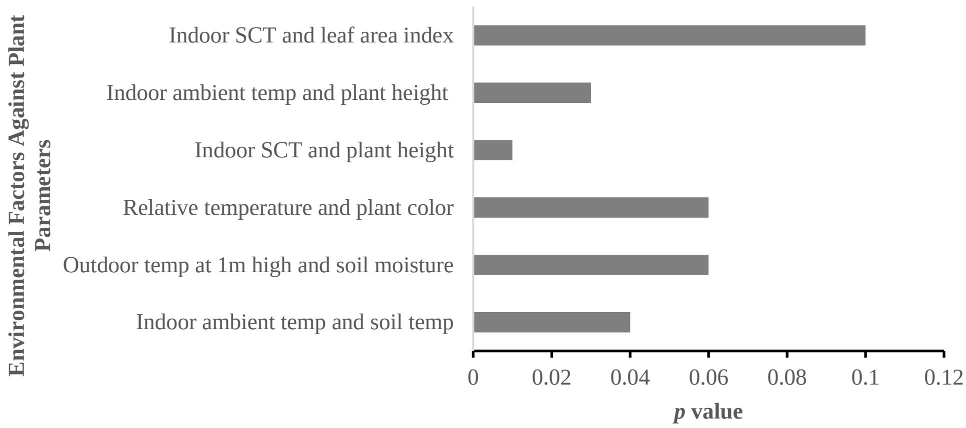


Figure 146. Statistical significance: *p* values for real-time zone 2 smart green roof environmental factors against plant parameters.

Note. SCT, surface ceiling temperature; temp, temperature.

As indicated by Tables 53, 54, and 55 corresponding to the p value relationships, over the monthly duration of the experiment, throughout the fluctuations occurring in LAI, plant height, and plant color, with an increase in these plant performance parameters, there is a conjunctive decrease in indoor surface ceiling temperature, indoor ambient temperature, and relative temperature, respectively. The opposite is also true, with observed decreases in plant parameters, a corresponding increase in environmental factors occurs, suggesting that due to the lack of adequate performance from the SGR, there is no detected effect on the climate conditions (Tables 53, 54, and 55).

Table 53. Real-time zone 2 SGR indoor surface ceiling temperature and LAI

	Mar-21	Apr-21	May-21	Jun-21	Jul-21	Aug-21	Sep-21	Oct-21	Nov-21	Dec-21	Jan-22	Feb-22
Indoor surface ceiling temp (°C)	24.58	28.95	30.37	30.47	33.37	30.31	29.99	28.77	26.42	22.01	21.58	21.06
LAI	0.50	0.55	0.40	0.25	0.50	0.75	1.50	1.50	0.15	0.60	2.00	2.20

Note. SGR, smart green roof; LAI, leaf area index; *p* value between indoor surface ceiling temperature and LAI = 0.10.

Table 54. Real-time zone 2 SGR indoor surface ceiling temperature and LAI

	Mar-21	Apr-21	May-21	Jun-21	Jul-21	Aug-21	Sep-21	Oct-21	Nov-21	Dec-21	Jan-22	Feb-22
Indoor ambient temp (°C)	24.89	29.95	31.54	32.52	36.61	32.12	31.68	31.02	26.59	22.11	22.01	21.89
Indoor surface ceiling temp (°C)	24.58	28.95	30.37	30.47	33.37	30.31	29.99	28.77	26.42	22.01	21.58	21.06
Plant heigh (cm)	20.71	19.71	16.57	16.14	20.70	21.60	23.00	24.40	20.10	23.50	28.60	28.60

Note. SGR, smart green roof; LAI, leaf area index; *p* value between indoor ambient temperature and plant height = 0.30; *p* value for indoor surface ceiling temperature and plant height = 0.01.

Table 55. Real-time zone 2 smart green roof relative temperature and plant color

	Mar-21	Apr-21	May-21	Jun-21	Jul-21	Aug-21	Sep-21	Oct-21	Nov-21	Dec-21	Jan-22	Feb-22
Relative temp (°C)	26.50	30.65	36.30	37.45	38.62	26.50	37.77	31.80	28.95	25.25	22.35	23.8
Plant color	4.00	3.43	2.49	1.71	3.20	3.50	3.70	3.50	2.10	3.60	4.00	4.00

Note. p value between relative temperature and plant color = 0.06.

If the observed reductions in indoor surface ceiling temperature, indoor ambient temperature, and relative temperature are taken collaboratively, a reduced urban heat island effect is suggested. This is owed to the plant performance stemming from the SGR, findings of increases in plant height, LAI, and darker plant colors. Roofs integrated with taller, denser, dark-colored plants will allow the building to be cooler compared to shorter, sparsely-covered, light-colored plants (Wong & Chin, 2018). The UHI effect varies and is strongly related to vegetation cover (plant leaf coverage) and meteorological conditions (Tzavali et al., 2015). This information provides basic integral knowledge to enhance plant selection appropriate to the hot arid climate conditions and integrate appropriate SGRs for optimum cooling performance.

Comparatively, with the observed characteristics of soil moisture and soil temperature, a statistically significant influence on outdoor temperature from 1m high and indoor ambient temperature was identified. This is a significant finding, as soil acts as an insulation layer. Thus, the soil moisture level has a contrastingly higher specific heat capacity as opposed to construction materials for the built environment, i.e., the bare roof. With rising soil moisture percentages, the outdoor temperature measured from 1m above the SGR descended (Table 56). Retaining the outdoor heat within the hydrogen bonds among water molecules is a feature of the water level in the soil moisture. As a result, water takes a long time to cool; thus, the heat energy takes longer to dissipate from the soil moisture back into the outdoor temperature.

Table 56. Real-time zone 2 SGR outdoor temperature at 1m high and soil moisture

	Mar-21	Apr-21	May-21	Jun-21	Jul-21	Aug-21	Sep-21	Oct-21	Nov-21	Dec-21	Jan-22	Feb-22
Outdoor temp at 1m high (°C)	25.98	30.01	36.12	37.13	38.08	38.36	36.11	31.14	27.47	23.80	19.56	22.47
Soil moisture (%)	NA	NA	41.76	53.86	47.61	48.21	50.42	36.90	49.03	49.15	45.85	46.15

Note. SGR, smart green roof; NA, not applicable; *p* value between outdoor temperature at 1m high and soil moisture = 0.06.

The lower indoor ambient temperatures may result from the statistically significant association with soil temperature decreases (Table 57). It was found that the uptake of outdoor heat resulting in lower soil temperatures caused the most effective inhibition of indoor ambient temperature. This indicates that the inclusion of an SGR improves indoor ambient temperature considerably due to the soil properties' ability to contain water, thus trapping heat for longer.

Table 57. Real-time zone 2 SGR indoor ambient temperature and soil temperature

	Mar-21	Apr-21	May-21	Jun-21	Jul-21	Aug-21	Sep-21	Oct-21	Nov-21	Dec-21	Jan-22	Feb-22
Indoor ambient temp (°C)	24.89	29.95	31.54	32.52	36.61	32.12	31.68	31.02	26.59	22.11	22.01	21.89
Soil temp (°C)	NA	NA	34.00	36.00	38.00	35.00	32.00	28.00	23.00	21.00	17.00	19.00

Note. SGR, smart green roof; NA, not applicable; *p* value between indoor ambient temperature and soil temperature = 0.04.

The analysis shows an increasing trend toward significance in the relationship between real-time environmental factors and plant performance parameters. These increasing trends are statistically significant during summer and winter. Strong *p* value evidence confirmed that SGRs, particularly plant height, alter indoor ambient and surface ceiling temperature. Outdoor and indoor environmental conditions are most likely attributable to a specific cause, the collective linked plant parameters that distinguish optimal SGR performance. However, the changes in wind speed are not substantial with SGR implementation.

7.3.3 Simulated Data Results Interpretation

The maximum simulated relative temperature surrounding the environment encompassing both bare and SGRs coincided on the 22 of July 2021, with a reading of 43.38°C (Table 45). As expected, the relative temperature rose in summer, with a correlative substantial drop in relative humidity. It is also evident and scientifically valid that relative humidity is higher in winter than in summer, a mean of 61.97% compared to a mean of 48.88%, respectively, due to warm air’s ability to possess more water vapor (Abu-Taleb et al., 2007).

Table 58 rejects the research hypothesis, showing an unexpected and reverse correlation between outdoor temperature and indoor surface ceiling temperature. It would be assumed that with a more effective SGR reducing the outdoor temperature by a higher value, you would observe higher differences between bare and SGRs for the indoor surface ceiling temperature. But the opposite occurred, most notably in September and November 2021 months. When the real-time SGR reduced the outdoor temperature at 1m by a mere 0.59ºC in September 2021, the highest reductions were observed in the simulated indoor surface ceiling temperatures for the zones; 0.90ºC in zone 1, 3.08ºC in zone 2, and 2.49ºC in zone 3. As opposed to when there is the highest difference between bare and SGRs in November 2021, a reduced outdoor temperature of 2.1ºC, with a less impactful influence on indoor surface ceiling temperature for the building zones, 0.50ºC in zone 1, 1.57ºC in zone 2, and 0.55ºC in zone 3.

Table 58. Monthly differences of simulated indoor surface ceiling temperature between bare and smart green roofs for zones 1, 2, and 3; and monthly difference of real-time outdoor temperature at 1m high between zone 2 bare and smart green roofs

	Simulated Indoor Surface Ceiling Temperature (°C)			Real-Time Outdoor Temp at 1m high (°C)
Month	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 2**
Mar-21	0.75	1.16	1.12	0.24
Apr-21	-0.09	0.69	2.02	0.20
May-21	0.10	2.24	0.94	0.36
Jun-21	0.18	1.86	-0.91	0.80
Jul-21	0.11	1.49	0.41	1.03
Aug-21	1.13	3.17	2.09	0.74
Sep-21	0.90	3.08	2.49	0.59
Oct-21	-0.28	3.21	1.32	1.21
Nov-21	0.50	1.57	0.55	2.10
Dec-21	0.71	0.78	1.02	0.93
Jan-22	0.37	1.04	1.00	0.13
Feb-22	0.38	1.02	1.06	0.14

However, it is surprising to note, supposing there is no effect on the building by SGR simulation, the different findings among zones. Zone 2 expresses the highest changes in differences from bare concrete to SGR, followed by zone 3 and then by zone 1 (Table 58). This poses the possibility that SGR performance caused these changes in indoor surface ceiling temperature, but not due to outdoor temperature influences. Further study and exploration are needed to determine which factor, or a mix of factors, had the highest impact on indoor surface ceiling temperature.

In support of the SGR's capacity to reduce conductive heat transfer, zone 3 experiences the greatest decrement of 3 in heat flux, and zone 2 heat flux is deducted by 1.94W/m^2; both observed findings in August 2021 (Table 59). While zone 1 differences between bare and SGRs is abated, noting a 0.40W/m^2 reduced heat flux due to the bare roof rather than the SGR. However, SGR ineffectiveness shouldn't be assumed as it accounted for 100% of the roof in zone 3, 78% in zone 2, and 0% in zone 1. This is a consequence of the building design having multiple floors.

Table 59. Simulated heat flux of zones 1, 2, and 3: differences between bare and SGRs

	Heat Flux (W/m^2)		
Month	**Zone 1**	**Zone 2**	**Zone 3**
Mar-21	0.48	0.30	0.14
Apr-21	-0.09	0.10	0.12
May-21	-0.48	0.79	1.30
Jun-21	-0.55	0.43	3.08
Jul-21	-0.27	1.82	2.07
Aug-21	-0.40	1.94	3.56
Sep-21	0.16	2.14	3.10
Oct-21	0.67	2.23	0.63
Nov-21	1.32	2.55	0.70
Dec-21	1.37	2.11	0.60
Jan-22	0.93	-0.09	0.60
Feb-22	0.73	1.86	0.61

As demonstrated by Table 60, LAI plays a significant role in indoor surface ceiling temperature. As shown, the highest indoor surface ceiling temperature is simulated in zone 3 (penthouse) of the building when the SGR is not performing. It is the closest to the roof, with the sun easily penetrating the upper floor. At its lowest, an LAI value of 0.25, exhibited in June 2021, simulates the indoor surface ceiling temperature in zone 1 as 35.48°C, zone 2 as 31.87°C, and zone 3 as 35.98°C. However, at an optimum performance of an SGR in comparison to a bare roof with an LAI of 2.2 in February 2022, a reduced indoor surface ceiling temperature in zone 1 is 24.42°C, zone 2 is 23.82°C, and zone 3 is 23.52°C. This is a measurable reduction with an improved LAI plant performance. LAI can reduce the SGR's surface temperatures by effectively shading the roof from incoming solar radiation (Mahmoud, 2015; Saeid, 2013). Leaves can provide shade by blocking incoming sunlight and distributing heat. As shown by Wong & Chin (2018), with greater air movement through smaller leaves than bigger leaves, leaves can stay cool. A high volume of foliage plays a significant role in SGR performance, influencing cooling effectiveness. Thus, this further displays the significant effect SGRs have on the building temperature and outdoor environment.

Table 60. Simulated smart green roof indoor surface ceiling temperature for zones 1, 2, and 3 and LAI

	Indoor Surface Ceiling Temperature (°C)			Leaf Area Index (LAI)
Month	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 2**
Mar-21	25.15	24.73	24.42	0.50
Apr-21	31.14	29.66	28.93	0.55
May-21	32.33	31.12	33.55	0.40
Jun-21	35.48	31.87	35.98	0.25
Jul-21	36.56	34.09	36.38	0.50
Aug-21	31.36	28.92	31.66	0.75
Sep-21	30.62	29.31	31.98	1.50
Oct-21	30.67	27.41	28.70	1.50
Nov-21	26.26	25.10	27.30	0.15
Dec-21	22.96	22.97	22.34	0.60
Jan-22	21.94	21.35	21.22	2.00
Feb-22	24.42	23.82	23.52	2.20

With the launch of smart irrigation, LAI began to recover, having been 0.25 in June 2021, 0.75 in August 2021, 1.5 in September 2021, and reached its highest canopy cover of 2.2 in February 2022 at the conclusion. With this gradual increase in LAI, an observed reduction in the simulated heat flux was seen, each zone having experienced different fluctuations and variations. Zone 3, the most impacted by an SGR, was reduced from 0.35 to 0.13, to 0.15, to -0.02, in those respective months (Table 61). The extent of the influence of the plant parameter, LAI, is seen to have eliminated the heat flux issue, thus, favorably towards user thermal comfort.

Table 61. Simulated smart green roof heat flux for zones 1, 2, and 3 and LAI

		Heat Flux (W/m^2)		Leaf Area Index (LAI)
Month	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 2**
Mar-21	0.70	0.32	0.10	0.50
Apr-21	0.80	0.27	0.17	0.55
May-21	1.20	1.33	0.19	0.40
Jun-21	0.76	2.50	0.35	0.25
Jul-21	0.92	0.77	0.24	0.50
Aug-21	0.70	2.32	0.13	0.75
Sep-21	0.33	0.89	0.15	1.50
Oct-21	0.25	0.24	0.11	1.50
Nov-21	0.01	0.23	0.09	0.15
Dec-21	-0.12	0.18	0.10	0.60
Jan-22	-0.12	0.25	-0.03	2.00
Feb-22	0.07	0.29	-0.02	2.20

The decrease in outdoor humidity might be due to the reduction of evaporation from land (Abu-Taleb et al., 2007). Table 62 shows outdoor humidity of 36.19% with an LAI of 0.25. As expected, the simulation generated a higher outdoor humidity, 65.22%, with an increase in plant foliage density of a simulated 2 LAI in January 2022.

Table 62. Simulated smart green roof of outdoor humidity and LAI

	Mar-21	**Apr-21**	**May-21**	**Jun-21**	**Jul-21**	**Aug-21**	**Sep-21**	**Oct-21**	**Nov-21**	**Dec-21**	**Jan-22**	**Feb-22**
Outdoor humidity (%)	62.63	57.16	44.11	36.19	49.99	49.35	51.87	61.46	58.90	65.77	65.22	61.86
LAI	0.50	0.55	0.40	0.25	0.50	0.75	1.50	1.50	0.15	0.60	2.00	2.20

Note. LAI, leaf area index.

The smallest *p* value, denoting the highest degree of statistical significance implying the influential occurrence is not due to chance, is 0.01 heat flux in zone 3 and LAI simulated data (Figure 147). The accompanying shading effects of a higher LAI and denser foliage are thus noted to be the highest influential characteristic controlling the SGR thermal performance (Parizotto & Lamberts, 2011).

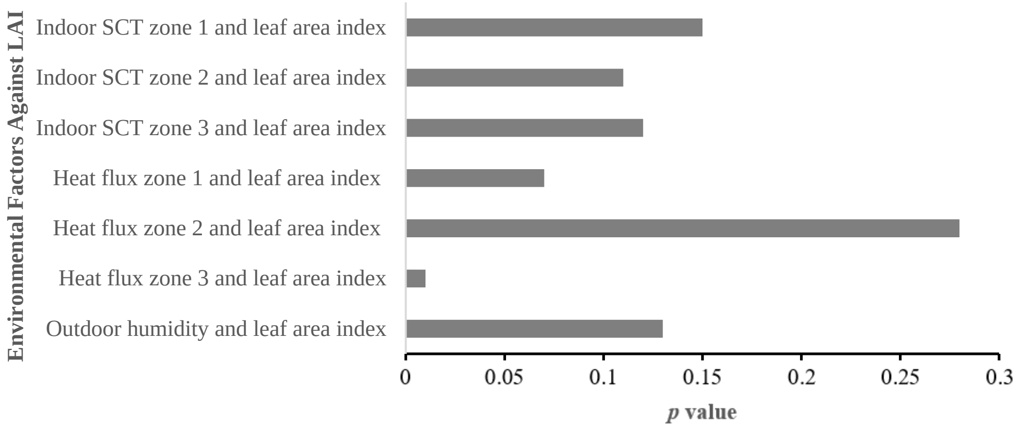


Figure 147. Statistical significance: *p* values for simulated environmental factors against LAI.

Note. SCT, surface ceiling temperature; LAI, leaf area index.

There is a complementarity between indoor surface ceiling temperature and plant height. Assessment of this complementarity can, in part, be explained in Table 63. With plant maturity achieved by maintenance, the plant naturally become taller. From 16.14cm in June 2021 to 28.6cm in January 2022, zone 1 indoor surface ceiling temperature experienced a simulated drop from 35.48°C to 21.94°C, zone 2 from 31.87°C to 21.35°C, and zone 3 from 35.98°C to 21.22°C. The largest reduction was observed in zone 3, a decrease of 14.76°C. Despite the zone 3 surface being in direct contact with solar radiation, it had the largest SGR coverage of 100%. This again confirmed that an extensive SGR could improve the roofing system, particularly effectively reducing indoor surface ceiling temperature. Thus, implementing an SGR reduces the indoor surface ceiling temperatures, enhancing user comfort and productivity inside the building.

Table 63. Simulated smart green roof indoor surface ceiling temperature for zones 1, 2, and 3 and plant height

	Indoor Surface Ceiling Temperature (°C)			Plant Height (cm)
Month	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 2**
Mar-21	25.15	24.73	24.42	20.71
Apr-21	31.14	29.66	28.93	19.71
May-21	32.33	31.12	33.55	16.57
Jun-21	35.48	31.87	35.98	16.14
Jul-21	36.56	34.09	36.38	20.70
Aug-21	31.36	28.92	31.66	31.60
Sep-21	30.62	29.31	31.98	23.00
Oct-21	30.67	27.41	28.70	24.40
Nov-21	26.26	25.10	27.30	20.10
Dec-21	22.96	22.97	22.34	23.50
Jan-22	21.94	21.35	21.22	28.60
Feb-22	24.42	23.82	23.52	28.60

The improvement in heat flux is a great indication of the enhanced indoor environment and comfort. As shown by Table 64, heat flux improves and is reduced over time with taller plants. Plant height is a component of SGRs and indicates their performance. With 16.14cm tall simulated plants in June 2021, simulated heat flux is high with 0.76W/m^2 in zone 1, 2.5W/m^2 in zone 2, and 0.35W/m^2 in zone 3. While, with 28.6cm tall simulated plants in February 2022, simulated heat flux is low with 0.07W/m^2, 0.29W/m^2, and -0.02W/m^2 in those respective zones. It is concluded that the SGRs parametric plant height allows for a lower heat flux in winter and summer months, thus, enhancing users' comfort in the building.

Table 64. Simulated smart green roof heat flux for zones 1, 2, and 3 and plant height

		Heat Flux (W/m^2)		Plant Height (cm)
Month	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 2**
Mar-21	0.70	0.32	0.10	20.71
Apr-21	0.80	0.27	0.17	19.71
May-21	1.20	1.33	0.19	16.57
Jun-21	0.76	2.50	0.35	16.14
Jul-21	0.92	0.77	0.24	20.70
Aug-21	0.70	2.32	0.13	31.60
Sep-21	0.33	0.89	0.15	23.00
Oct-21	0.25	0.24	0.11	24.40
Nov-21	0.01	0.23	0.09	20.10
Dec-21	-0.12	0.18	0.10	23.50
Jan-22	-0.12	0.25	-0.03	28.60
Feb-22	0.07	0.29	-0.02	28.60

Analyses of fluctuations in year-long seasonal relative humidity are presented in Table 65. The outdoor humidity curve follows the plant height curve in the graphical representation. Again, the notion that more plant material increases the moisture in the surrounding air is expressed.

Table 65. Simulated smart green roof outdoor humidity and plant height

	Mar-21	**Apr-21**	**May-21**	**Jun-21**	**Jul-21**	**Aug-21**	**Sep-21**	**Oct-21**	**Nov-21**	**Dec-21**	**Jan-22**	**Feb-22**
Outdoor humidity (%)	62.63	57.16	44.11	36.19	49.99	49.35	51.87	61.46	58.90	65.77	65.22	61.86
Plant heigh (cm)	20.71	19.71	16.57	16.14	20.70	21.60	23.00	24.40	20.10	23.50	28.60	28.60

Plant height is statistically significant with indoor surface ceiling temperature, more so in zones 2 and 3 with a 0.01 *p* value than in zone 1 with a 0.02 *p* value. Plant height is also trending toward significance when compared to heat flux, as seen in Figure 148, with a 0.06 *p* value in zones 2 and 3. This shows the significant effect SGRs have on the building temperature and the reduction of heat transfer. To compare plant height *p* values against *p* values associated with the LAI plant parameter, statistically, plant height is a more significant factor affecting environmental factors in all three zones. This is an interesting statistical discovery between LAI and plant height, suggesting that plant height was more significant, but not necessarily more important, at preventing a high indoor surface ceiling temperature and reflecting heat flux. This resulted in a warped perception of the implementation and effectiveness of the plant parameter components of SGRs in hot arid climates.

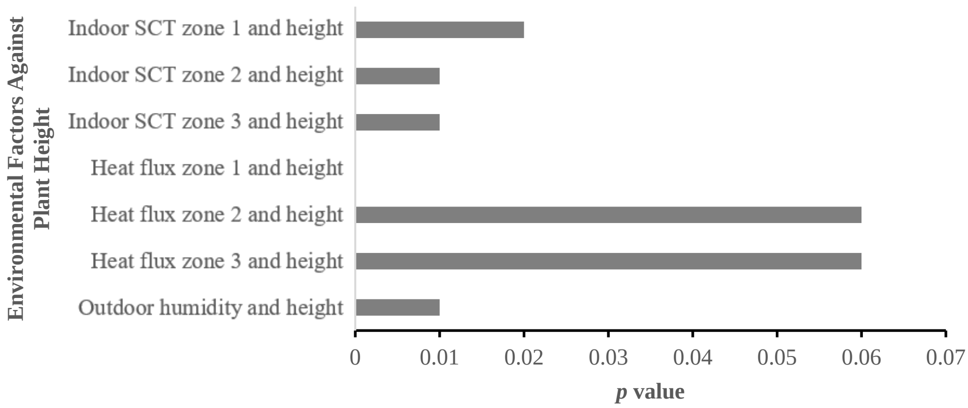


Figure 148. Statistical significance: *p* values for simulated environmental factors against plant height.

Note. SCT, surface ceiling temperature.

Statistical significance analysis identified that there are no statistical significances between indoor surface ceiling temperature and volume, indoor surface ceiling temperature and soil moisture, heat flux and volume, and heat flux and soil moisture, for any of the three zones of the office building (Figure 149). Although it only constitutes an 8% probability of it occurring by chance for zone 3, it inclines that passive cooling could be attributed to the soil moisture level of the SGR. Providing evidential statistics on the enhanced benefits of the smart irrigation soil moisture sensor.

As for the remaining *p* values, all well above 0.24, the research study's results on associations between indoor surface ceiling temperature and heat flux with both volume and soil moisture are not statistically significant. The null hypothesis is accepted in this case, and no provable significant effect is assumed.

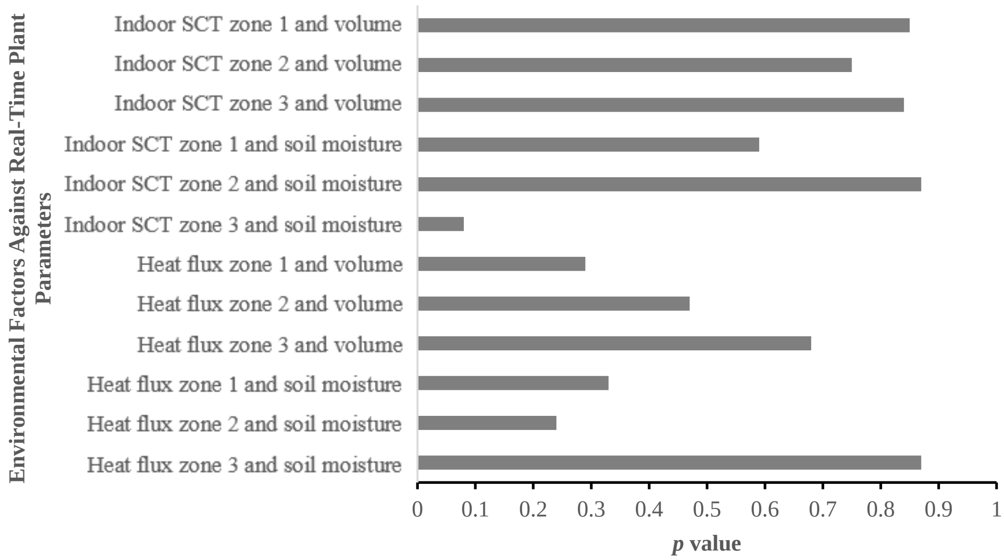


Figure 149. Statistical significance: *p* values for simulated environmental factors against real-time plant parameters.

Note. SCT, surface ceiling temperature.

The simulated total sum of electricity consumption, also known as sensible cooling required, between the bare envelope and the use of an SGR on the office building was 2.11kWh/m^2, 22.02kWh/m^2, 33.31kWh/m^2 for thermal zones 1, 2, and 3, respectively (Figure 150). This increase in reductions from zone 1, 2, to 3 corresponds to the effects of the SGR, as 100% of the zone 3 roof has been implemented with an SGR, while the zone 2 roof only constitutes 78% SGR implementation. While data extracted on SGR performance against the bare roof shows that zone 1 is comparatively less effective in reducing sensible cooling energy demands than bare roofs. Thus, it is construed that zone 3, followed by zone 2, acquires the best energy consumption performance concerning energy saving due to the presence of the SGR. That is a 20.09% savings in electricity consumption per annum by adding a vegetated layer.

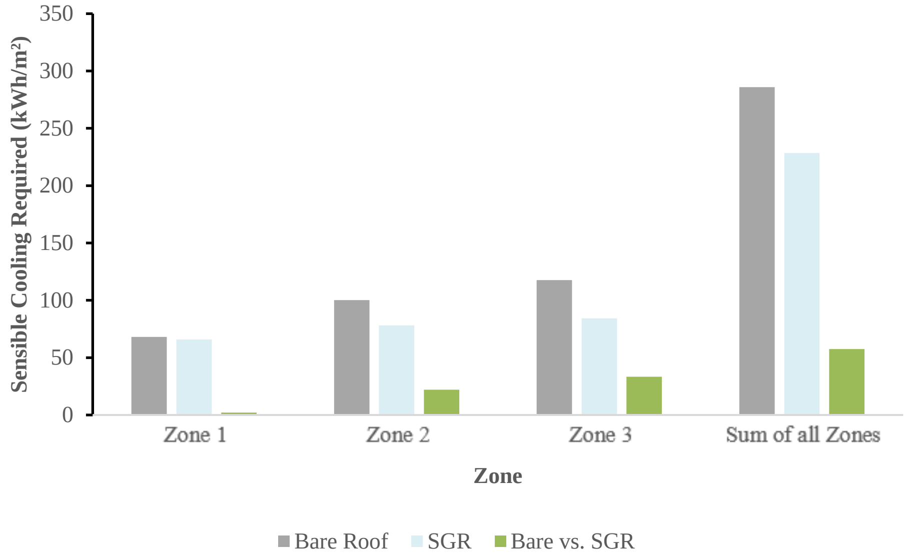


Figure 150. Annual energy consumption of the total sum of sensible cooling required for zones 1, 2, and 3 bare and smart green roofs.

Note. kWh/m^2, kilowatt hour per square meter; SGR, smart green roof.

For each bare roof zone and SGR zone energy simulation, a total annual energy cost was calculated, as presented in Figure 151. The energy savings reached a total of QR 1819.93 in the office building because of the application of an SGR system. The energy utility rates were used in these calculations. These bills were based on the 2021 commercial electricity tariffs used by Qatar General Electricity and Water Corporation (KAHRAMAA): 0.13QR/kWh for electricity consumption between 1-4000kWh and 0.17QR/kWh for electricity consumption between 4001-10000kWh. The energy cost savings were further calculated, depending on utility rates that can vary depending on the geographic region and global utility prices. Energy cost was saved by 21.61%

annually through the SGR affecting the first floor (zone 2) and the penthouse (zone 3), thereby acting as insulation for the structure of the building.

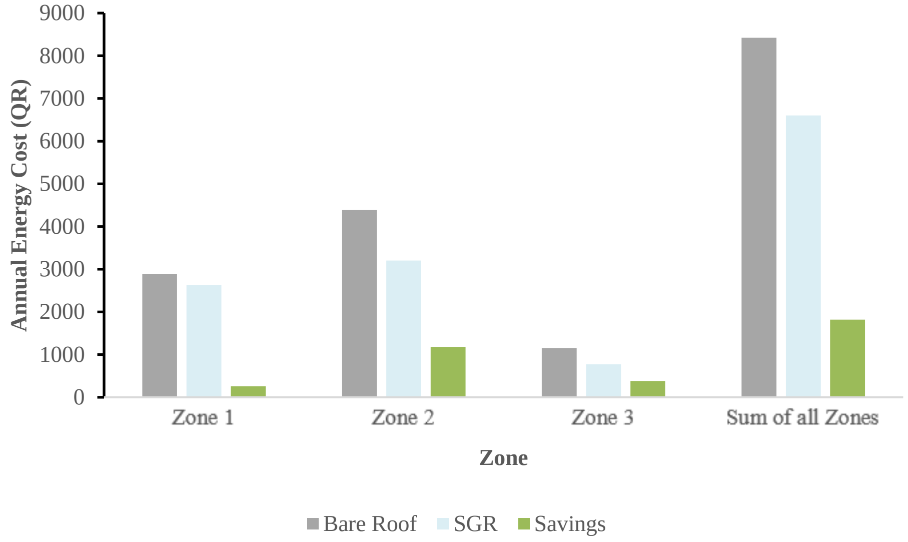


Figure 151. Annual energy cost for zones 1, 2, and 3 bare and smart green roofs.

Note. QR, Qatari Riyal; SGR, smart green roof.

Another function of SGRs in terms of energy efficiency is to prevent the heating of indoor spaces of buildings. An increase in plant height and LAI values corresponds to energy consumption reduction in summer. This effectively ensures energy and peak electricity demand is saved primarily due to the plants in the SGR, as shown by the works of Wong and Chin (2018) for green roofs without a smart application. In addition to reducing building cooling energy consumption, the SGR allows to reduce peak electricity demand, facilitating two outcomes. Primarily, with smaller peak demand, the mechanical cooling equipment for a building will require a smaller capacity, typically less expensive. Secondly, depending on the building size and amount of equipment in the building, keeping the equipment turned off or avoiding higher temperatures that require high loads of electricity, electricity costs will be reduced despite longer use

(Abikarram, 2017). This research did not include quantifying energy savings concerning these SGR strengths.

The heat flow between the building and its environment generates energy demand through air conditioning. The heat flow was estimated by the sum of heat entering and leaving the roof's surface, which was obtained by the heat flux over time. Green roofs reduce the heat flux through the building envelope, where the growing medium provides higher insulation, thermal mass, plant shading, and retention of moisture for evaporative cooling (Theodosiou, 2003). These elements decrease the room's heat gains, thus reducing the room's cooling demand, where there is a reduction in both solar and conductive heat gains and losses, according to GSAS Building Typologies Guidelines 2019 and ASHRAE 90.1. Results analyzed in Table 66 illustrate this phenomenon.

Table 66. Relationship between annual cooling loads and thermal characteristics (U-Value, R-Value, and thermal conductivity) of bare and smart green roofs

	Bare Roof	**Smart Green Roof**
Annual Cooling Loads (kWh)	285.87	228.43
U-Value (W/m^2K)	0.58	0.44
R-Value (m^2K/W)	1.72	2.27
Thermal Conductivity (W/mK)	0.17	0.31

U-Value distinguishes the heat transfer rate through the building, while the R-Value measures the building insulation's efficiency in preventing this heat flow. The SGR has a lower U-Value, and higher R-Value compared to the bare roof (Table 66). With a decreased U-Value, as a direct result of reduced heat transfer, the cooling load diminishes ostensibly due to the higher insulation R-Value association. Thus, the SGR functionally decreases U-Value, correlated with a lower heat flux (Vilar et al., 2021). A lowered U-Value associated with a higher R-Value denotes greater insulation performance and, thus, more savings on cooling costs.

However, it is notable that the thermal conductivity of the SGR is higher than that of the bare roof (Table 66). The association between U-Value, R-Value, and thermal conductivity naturally states that with a low U-Value, there is more insulation (R-Value) and, thus, less heat loss (thermal conductivity). However, this characteristic relationship is not observed for SGRs. This incidental design could be accredited to the manual calculation of thermal conductivity, considering the thickness of the materials and the type of materials. The thickness of the bare roof is 0.3m, while the SGR is 0.71m. Furthermore, thermal conductivity is attributed to how fast heat will move across a material, and as a result of the plastic pods having higher thermal conductivity, thermal performance is worsened.

Peak outdoor temperature coincides with peak heat flux, falling on the 22nd of July, 2021. This peak day is studied to determine the SGR parametric effect on heat flux when it is the hottest day of the studied year. It is noted from simulated data that heat flux is higher on upper floors due to the higher heat index in summer. This higher index is due to the sun penetrating the upper floors and making them more prone to warmer temperatures. The differences in heat flux for zones 1, 2, and 3 between bare and SGR are -0.38W/m^2, 2W/m^2, and 3.3W/m^2, respectively (Table 67). The higher heat flux differences from zone 2 and 3 depict the reduction of heat transfer between bare and SGRs, which is inevitably due to SGRs; thus, enhancing users' comfort in the building.

Table 67. Hourly simulated heat flux showing zone 1, 2, and 3 bare and smart green roofs on 22 July 2021 at summer peak

Time on the 22nd of July 2021 (hour)	Heat Flux (W/m^2)					
	Bare Roof			Smart Green Roof		
	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3
1	-1.00	1.94	1.33	-0.22	0.73	-1.00
2	-1.15	1.82	1.21	-0.33	0.61	-1.12
3	-1.78	1.23	0.59	-0.80	0.14	-1.60
4	-2.33	0.70	0.02	-1.21	-0.28	-2.06
5	-1.46	1.65	0.86	-0.61	0.32	-1.58
6	-1.31	1.78	0.91	-0.51	0.38	-1.58
7	-1.12	2.00	1.14	-0.37	0.54	-1.43
8	-0.96	2.22	1.43	-0.25	0.69	-1.23
9	-0.80	2.43	1.69	-0.13	0.84	-1.05
10	-0.62	2.64	1.96	-0.01	1.14	-0.65
11	-0.23	4.10	3.63	0.54	2.44	0.69
12	1.92	6.38	6.13	1.97	3.55	1.75
13	3.11	7.73	7.53	2.82	4.35	2.53
14	3.54	8.48	8.25	3.15	4.87	3.02
15	3.48	8.54	8.28	3.11	4.92	3.05
16	3.24	8.35	8.09	2.92	4.80	2.93
17	3.85	8.66	8.41	3.33	5.04	3.17
18	4.19	8.32	8.08	3.51	4.76	2.89
19	2.08	5.27	4.83	1.82	2.79	1.05
20	0.42	3.39	3.00	0.77	1.78	0.15
21	-0.08	2.82	2.40	0.40	1.41	-0.24
22	-0.66	2.22	1.76	-0.01	0.98	-0.69
23	-1.10	1.77	1.25	-0.33	0.65	-1.06
24	-1.22	1.68	1.10	-0.41	0.56	-1.16

Although zone 1 SGR has a higher heat flux than its bare roof, it was predicted as there would be no green rooftop on top of the ground level (zone 1) due to a lack of a roof. As for zones 2 and 3, it is also significant to note that the SGRs plant performance, analyzed through an LAI of 0.50 and plant height of 20.7cm on the peak day, 22 July 2021, shows that the plant's influence on heat flux is not at full capacity. The LAI measurement denotes a medium state of density in comparison to the average yearly LAI of ~0.91. This indicates that if the SGR performed in a denser and improved state, the plants could improve the heat flux of the building zones. LAI and plant height are determinately not optimum, hence the lack of a juxtaposition between heat flux and outdoor temperature.

Moreover, it is further described that the total sum differences of sensible cooling between the bare and SGR for zone 1, 2, and 3 are 0.02kWh/m^2, 0.11kWh/m^2, and 0.21kWh/m^{2,} respectively (Table 68). Thus, it is construed that zone 2 and 3 acquire the best energy consumption performance with respect to energy saving due to the presence of the SGR. While data extracted on SGR performance for zone 1 shows that it is comparatively less effective in reducing sensible cooling energy demands than bare roofs. This is associated with the SGR amount as zone 1 has 0%, while zone 2 consists of 78%, the remaining 22% of the roof consists of the penthouse, and zone 3 is entirely 100% applied with an SGR.

Table 68. Hourly simulated energy consumption of cooling required on 22 July 2021 for bare and smart green roofs for zone 1, 2, and 3 during summer peak

Time on the 22nd of July 2021 (hour)	Sensible Cooling (kWh/m^2)					
	Bare Roof			Smart Green Roof		
	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3
1	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00
5	0.02	0.02	0.03	0.02	0.02	0.02
6	0.02	0.02	0.03	0.02	0.02	0.02
7	0.02	0.03	0.03	0.02	0.02	0.03
8	0.02	0.02	0.02	0.02	0.02	0.02
9	0.01	0.01	0.01	0.01	0.01	0.01
10	0.01	0.01	0.01	0.01	0.01	0.01
11	0.01	0.03	0.03	0.02	0.03	0.03
12	0.03	0.04	0.05	0.03	0.03	0.03
13	0.03	0.04	0.05	0.02	0.03	0.02
14	0.03	0.05	0.06	0.03	0.03	0.02
15	0.03	0.05	0.06	0.03	0.03	0.04
16	0.03	0.05	0.06	0.03	0.03	0.04
17	0.04	0.05	0.06	0.03	0.04	0.04
18	0.04	0.05	0.08	0.03	0.04	0.04
19	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00	0.00
Sum	**0.34**	**0.47**	**0.58**	**0.32**	**0.36**	**0.37**

7.4 Conclusion

This chapter presented a holistic investigation of SGR benefits using a combined qualitative and quantitative (real-time and simulation based) integrative results interpretation. This was performed using an extensive lightweight green roof focused on the smart application. It was also confirmed that as a consequence of SGRs, sensible cooling energy demand was reduced, directly linked with enhanced users' thermal comfort. The analytical interpretations revealed that SGRs could harbor potential environmentally advantageous outcomes.

As a first assessment of their complexity, SGRs influence the mitigation of ensuing extreme summer heat experienced by users indoors of a building; however, economic fallbacks such as construction, installation, and maintenance costs of the SGR should be considered.

The quantitative data analysis and interpretation divulged users' predicted mean vote, metabolic rate reading, and clothing insulation values. Through user questionnaire responses and qualitative experts' interview feedback, it was discovered that outdoor temperature is easily penetrable into the three office buildings affecting the thermal comfort of the users'. This is primarily attributable to poor insulation and improper building design. Thereby, implementing an SGR expresses the utmost beneficial outcomes to the thermal environment of the building to improve indoor building temperature, thus affecting a user's thermal experience.

Results interpretations show that the factors, such as temperature, humidity, heat flux, U-Value, R-Value, and thermal conductivity, are associated and improve within the building envelope with SGR use. A decrease in building energy consumption with a consequential improvement to user thermal comfort is divulged from data findings.

Interesting findings were uncovered during quantitative data investigation from real-time and simulation studies. The interpretations derived from obtained results are consistent and amplify other research that states green roofs implemented on rooftop buildings mitigate high indoor temperatures (Cirrincione et al., 2020; Kumar & Kaushik, 2005; Wong & Chin, 2018). It was found that the outdoor climatic conditions influence the insulation performance of the extensive SGR.

Employing a smart-based approach for the irrigation system of the green roof has proven effective in conserving water consumption, and reducing the volume of water required to irrigate the plant system. Technological advancements have made it possible to monitor plant sustenance through soil temperature and moisture measurements via sensors. This information is significant to monitor and supply the right amount of water for plants to thrive. Sustainable measures are needed in climate conditions with reduced amounts of rainfall, calling for a smart integrative irrigation system for water conservation. The data shows that water volume consumption is significantly reduced with a smart application and remote IRRIOT use. This is a significant finding as the dual interplay of the sensors and automated drip irrigation system has the potential to abide by contactless regulations that arise from outbreaks or pandemics.

With varied LAI values, representing the plant leaf coverage and foliage in a canopy, and plant heights, it was found that the SGR with larger LAI and taller vegetation was able to maintain lower indoor temperatures, reduce heat flux, and the canopy's relative temperature, also seen in the research works of Kumar and Kaushik (2005). LAI and plant height greatly influence the shading effects, particularly during summer. In addition, the darker plants' leaf color enables a higher amount of solar radiation to be absorbed and reflected, per Cirrincione et al. (2020) study. Thus, the research findings are supported by the literature review data.

Moreover, LAI, plant height, and soil moisture positively affect the SGR’s thermal performance and behavior, reducing the U-Value and amplifying the R-Value, resulting in improved insulation having a direct influence on a diminished amount of sensible cooling energy demand. The SGR thus reduces the high solar absorptivity and considerably reduces the indoor and outdoor surface temperature gradients, thus increasing the users' thermal comfort level concerning the indoor environment quality. The office building with an SGR tended to be cooler than the bare roof. Hence, associating improved and maintained plant and SGR performance with enhanced environmental factors (reduced indoor and outdoor temperatures, reduced heat flux), reduced cooling energy requirement, and better user thermal comfort, as causation rather than just correlation.

The simulation tool, DesignBuilder, has limited capabilities in calculating exact plant performance. Thus, the values for LAI, plant height, and soil moisture were manually inputted per month according to the collected real-time experimental raw data. Furthermore, DesignBuilder is incapable of simulating plant color and soil temperature plant performance parameters as there is no dedicated data entry cell to input data variations. With that said, despite color being a variable in DesignBuilder, color data is used for display purposes when plant texture is unavailable. DesignBuilder lacks the ability to mimic varying plant color influences on environmental factors. With the adoption and integration of a universal color classification system specific to plants, DesignBuilder will be able to produce simulated data associated with the main points of study, indoor surface ceiling temperature, and heat flux. Moreover, real-time data is concerned with zone 2, while simulated data is concerned with all zones of the building; thus, the reasoning as to consider only peak day to simulate values with DesignBuilder.

For the relationships that did not reach statistical significance, this might be accounted for by a small sample size. Additions of more soil moisture sensors in multiple and different spaces, an increase in the size of the SGR, or the conduct of the real-time experiment over a longer duration are potential methods to increase the sample size. These further studies may be needed to verify the importance and statistical significance between plant performance parameters and environmental factors. Collecting and assessing a myriad of other environmental factors, such as reducing carbon dioxide emissions and mitigating urban heat island effect, may open new aspects to SGRs that can be investigated for future studies (Arabi et al., 2015; Hirano et al., 2019; Kuronuma et al., 2018; Li & Babcock, 2014; Sahnoune & Benhassine, 2017).

Further research on different SGR designs, for example, changing substrate thickness as literature shows that there might be an influence. Kazemi and Courard (2021) investigate the effects of substrate thickness and drainage layers on the thermal behavior of extensive green roofs. Their accumulated results incur that an increase in substrate and drainage layers thicknesses resulted in a decrease in internal ceiling temperature and a reduction in its fluctuation, owing to high thermal mass and moisture content of the substrate and drainage layers, correspondingly improving thermal resistance of the green roof. Another research by Shao et al. (2021) examined the thermal performance of the extensive and intensive substrate. They concurred with similar findings that an increase in the thickness of the substrate also led to a reduction in ceiling temperature and improved insulation performance. They were also owing to the increased thermal capacity of the substrate as substrate mass increases. So, seeing if deviations to other parametric components of an SGR have a similar effect in hot arid climates is of interest.

In addition, the thermal conductivity of the SGR (plastic pod) is not on par with its U-Value and R-Value; thus, exploration of material use might be worth looking into. Further study involving two neighboring office buildings, one without any manipulation (i.e., a bare roof), the other implemented with an SGR over the entire building roof area, to observe the effect of its entire application. Investigations into adjacent urban buildings to ensure both buildings experience the same urban climatic conditions.

The following and final chapter of the thesis concludes and outlines a set of SGR design recommendations to develop and implement an SGR capable of withstanding and persevering in hot arid climates. Chapter 8 further represents recommendations for future research directions of the project, which could potentially open new questions for the research in this field of SGRs. Accordingly, future studies will need to identify the effect of other parameters that have the potential to be altered with SGR enforcement. An overlap among these parameters with SGR performance should also be scrutinized. The next chapter also highlights study limitations and key challenges experienced when undertaking this research. Therefore, it is paramount to distinguish an optimum design of an SGR to customize an appropriate vegetation selection and tailor a strategy to combat and reduce the buildings energy consumption for heating, mainly during summer of the hot arid climate of Qatar. The results interpretation of the research findings thus shapes a solution to the three research questions on designing, developing, and implementing an SGR.

CHAPTER 8: CONCLUSION AND SMART GREEN ROOF DESIGN RECOMMENDATIONS

8.1 Conclusion

This study investigated the influence of a modular green roof system on the thermal behavior of building envelopes and its impact on the indoor environment in Qatar. The modular smart system aims to design, develop, and implement a sustainable system for smart green roofs (SGRs) by reducing heat loss, reducing energy use, and enhancing the user's thermal comfort. Relevant literature papers have been reviewed to understand and select an appropriate smart irrigation system for the use-case's green roof (Al-Ali et al., 2020; Krishnan et al., 2020; Liao et al., 2021; Mirás-Avalos et al., 2019; Podder et al., 2021; Tiglao et al., 2020; Zhao et al., 2018). Accordingly, it was apparent that there exists a lack of studies regarding a smart-based irrigation system for green roofs.

Qatar is a booming and developed country; however, it experiences extremely hot seasons throughout the year. Thus, its urban environment and buildings need to be climate-adaptable to sustain and improve the users' thermal comfort. There is a clear lack of green spaces in densely populated urban areas in the Gulf and MENA region. A reason for the lack of green roof use and implementation is the misconception that these systems are difficult to design and construct in coherence with the building design. Hence, the research study's aim involved designing, developing, and implementing SGRs in the hot arid region of Qatar to discover a balanced solution between energy consumption and users' thermal comfort. The thermal comfort of the use-case was examined using a combined methodology, employing real-time and building performance simulation.

Integrating the extensive SGR onto the office building, with benefits including its lightweight feature and emphasis on developing self-sustaining communities while requiring no intensive maintenance. This is a beneficial green technology that urban planners, designers, architects, and engineers can apply on new and existing roofs in Qatar. This study was conducted following real-time experimental tools and techniques to determine the properties based on native plant species rather than adopting from literature. These vegetation properties in this research included leaf area index (LAI), plant height, plant color, soil moisture, soil temperature, U-Value, R-Value, and thermal conductivity. While the counterpart environmental factors consisted of humidity, wind speed, indoor and outdoor temperatures, and heat flux. Statistical significance was employed because p values below the 5% threshold were primarily amongst LAI, plant height, indoor temperatures, and heat flux.

The building model developed in DesignBuilder was calibrated against real-time data during summer and winter seasons and the one-year period. With the aid of statistical tools, the model was calibrated. Then, a one-year simulation was conducted using the calibrated model to perform parametric analysis for the dual enhancement of thermal comfort and energy demand reduction. A simulated green roof was compared against a bare roof. The study's results revealed statistically significant findings that are potentially useful for building engineers, architects, and urban planners to establish a direction for future improvement of indoor comfort in the hot arid region.

The smart and sustainable green roof allowed for easy maintenance and system monitoring for the end users. The employment of IRRIOT and remote monitoring sensors allowed to detect soil moisture and sustainably dimension the water supply for the intended use. It was discovered that optimal soil conditions ranged from 40-45% irrigation needs depending on the climatic weather conditions. After adapting to the smart irrigation system and using the soil moisture sensor, an important finding saw a reduction in total water volume used for irrigation, from 1187L to 37L. This significant drop, accountable to the smart digital application, bodes well for the SGR system's self-sufficiency, independency, and ability to provide touchless means in the event of a pandemic.

Overall, the obtained results highlight the effectiveness of the SGR system when compared with the bare roof under the same environmental conditions. The gradual observed increases in LAI influenced the building by reducing the maximum indoor air temperature, resulting from the effects of solar shading and evapotranspiration by the vegetative foliage. Given the foregoing, these factors depend on the selected plant types, thus decreasing high indoor temperatures during summer and, consequently, the cooling energy consumption. Thus, the choices made for SGR use improve the building’s energy performance and, consecutively, the user thermal comfort, notably in hot arid Qatar. The study focused on comparing outdoor temperatures, indoor temperatures, humidity, and heat flux between a bare and SGR with respect to three zones, ground, first, and penthouse, for one year. The research concludes the following for the studied SGR system when compared to a bare roof:

- Introduces denser foliage, thus contributing to higher outdoor and indoor humidity over the year.
- Reduces the outdoor temperature at 1m high by 0.79°C (2.12%) in the summer and 1.83°C (6.95%) in the winter (real-time zone 2).
- Attenuates indoor temperatures upon higher LAI, taller plants, and improved substrate conditions.
- Reduces the indoor ambient temperature by 1.54°C (4.51%) in the summer and 0.47°C (1.88%) in the winter (real-time).

- Reduces the indoor surface ceiling temperature by 1.33°C (4.17%) in the summer and 1.40°C (5.60%) in the winter (real-time).
- Reduces the indoor surface ceiling temperature zone 1 by 0.78°C (2.35%), zone 2 by 3.50°C (10.62%), and zone 3 by 3.16°C (9.31%) in the summer, and zone 1 by 0.71°C (2.76%), zone 2 by 3.60°C (14.05%), and zone 3 by 3.80°C (14.77%) in the winter (simulated data).
- Generates statistically significant relationships in both the real-time experiment and simulation; for real-time, a *p* value of 0.06 between relative temperature and plant color, a *p* value of 0.06 between outdoor temperature at 1m high and soil moisture, and a *p* value of 0.04 between indoor ambient temperature and soil temperature.
- Produces trending towards significance simulated data findings for zone 3: a *p* value of 0.12 between LAI and indoor surface ceiling temperature, and a *p* value of 0.06 between plant height and heat flux; and statistically significant associations for zone 3: *p* value of 0.01 between LAI and heat flux, *p* value of 0.01 between plant height and indoor surface ceiling temperature.
- Produces trending towards significance simulated data findings for zone 2: a *p* value of 0.11 between LAI and indoor surface ceiling temperature, a *p* value of 0.28 between LAI and heat flux, and a *p* value of 0.06 between plant height and heat flux; and statistically significant associations for zone 2: *p* value of 0.01 between plant height and indoor surface ceiling temperature.
- Reduces the heat flux through the roof by 0.47W/m^2 (16.00%) in the summer and 0.42W/m^2 (68.85%) in the winter (real-time zone 2).
- Reduces heat flux in zone 1 by 0.42W/m^2 (43.30%), zone 2 by 2.76W/m^2 (88.75%), and zone 3 by 2.56W/m^2 (93.10%) in the summer, and zone 1 by

0.40W/m^2 (65.57%), zone 2 by 0.76W/m^2 (90.48%), and zone 3 by 0.64W/m^2 (98.46%) in the winter (simulated data).

- Improves the user's thermal comfort in indoor spaces by decreasing and delaying heat flux.
- Increments the plant's LAI and height to reduce the cooling loads and the total energy consumption, reducing the need for air conditioning.
- Produces a passive cooling effect due to lush greenery with an energy saving of up to 20.09% and annual energy cost savings reaching 21.61% (simulated data).

Furthermore, the reductions in outdoor temperatures will lower the thermal stress on the building, inducing a positive impact on envelope durability (Rosasco & Perini, 2019; Santamouris, 2014). Simulated findings revealed better thermal efficiency for zone 3, followed by zone 2 and then zone 1. And despite simulated peak climate and the notion that the greenery may not be sustained, the SGR decreases heat flux, enhancing thermal comfort and reducing cooling energy demands. Among other confounding variables, it was found that the thickness and degree of foliage coverage influence the thermal properties of the SGR, with optimum performance at an LAI of 2.2, plant height of 28.6cm, and substrate thickness of 20cm. Cohesively, plant performance parameters increase the thermal delay between the outdoor and indoor temperatures, mitigating the heat flux (Andric et al., 2020; Shao et al., 2021; (Parizotto & Lamberts, 2011; Velasco, César, & Srebric, 2009).

The associated energy consumption is diminished to enhance indoor thermal comfort concerning the predicted mean vote. The electricity consumption in terms of cooling required for the bare roof of the office building was 285.87kWh/m^2 annually, while it was recorded at 228.42kWh/m^2 when a vegetated layer was added, having implemented an SGR system. With a green vegetated layer, annual electrical energy consumption is reduced by 20.09% per annum. The SGR also had a lower U-Value and higher R-Value, signifying improved insulation performance. This reflects an annual economic saving of QR 6601.31.

The previous chapter symbiotically coordinates to calibrate a suitable design for sustainable building components, namely SGRs, for implementation in Qatar's hot arid urban environment. Successful calibration of DesignBuilder categorized it as a reliable simulation tool, generating data from a base line directive to conduct SGR thermal performance studies. This data included indoor and outdoor temperatures, thermal performance of heat flux, and energy consumption.

A host of recent studies, each with a specified means of quantitative assessment, have revealed the multitude of environmental (mitigating the urban heat island effect, improving thermal performance, energy consumption, reducing air pollution, reducing noise pollution, positive impacts on hydrology, and increasing habitat biodiversity), economic, social, and aesthetic advantages to green roofs (Abass et al., 2020; Athemes, 2017; Bevilacqua, 2021; Carson et al., 2013; Santamouris, 2014; Suszanowicz & Kolasa-Więcek, 2019; Vanstockem et al., 2018). To date, the notion of an SGR has barely been explored. Still, the benefits from a remote smart system suggest that further recognition may be uncovered by extensive studies, leading to a finding of a much broader application than currently examined. Technological progress, specifically in irrigation coupled with maintenance, will quickly allow for wireless improvements at depths not previously attained. This review highlighted the paucity of knowledge on green roofs that have a smart application. The characterization of design strategies and functional roles of the vast implications to SGR application will surely become one of the most significant and functional endeavors in future SGR research, with great application potential. Hence, the concept of SGRs is an enormous unchartered architectural sustainable territory awaiting our attention.

In conclusion, an SGR is an effective, sustainable means to contribute to improving buildings' thermal performance in hot arid climates to improve thermal comfort for users. The results of this dissertation research study show that SGRs are practical and applicable in Qatar. Study findings set a premise to formulate a smart-based green roof to construct sustainable smart buildings and cities. The remainder of part 3 outlines a set of SGR design recommendations, and future research directions for sustainable SGR design, addresses study limitations, and sets out possible future research.

8.2 Smart Green Roof Design Recommendations

The dissertation investigated and analyzed various plant performance parameters and their corresponding effects on environmental factors, energy consumption, and thermal comfort. Design recommendations for SGRs to accommodate Qatar’s hot arid environment were thus established. The research study focuses on designing, developing, and implementing an SGR that can be used in Qatar’s hot arid region. Through a series of recommendations, effective SGRs are offered as a guide for use by urban planners, developers, architects, engineers, decision-makers, and researchers to evaluate their design and create sustainable-lively urban streets (Wong & Chin, 2018).

SGR installation must be considered in the inception stages of building design and construction to account for the additional weight of the green roof and associated costs, as well as the scale of the building and built man-made environment. The use-case studied an existing office building consisting of the ground floor, first floor, and penthouse; thus, due to the building design, these levels were zone categorized to evaluate the effect of the SGR on each zone. As per real-time and simulated results, the zones with plant coverage showed efficient SGR capacity. This concept thus limits SGR implementation to low-rise buildings, including mosques, educational institutions (universities or schools), shopping malls, and restaurants. The latter may take advantage of the SGR and plant edible gardens, using these planted herbs, vegetables, and fruits in their menu items (Osmundson, 1999).

On another note, the UHI effect is more prominent at a certain height of low-rise buildings. SGRs reduce indoor temperatures, heat flux, energy consumption, and costs, and they also reduce the UHI effect. The green roof can significantly reduce higher temperatures in urban areas, as experimented with and simulated in the use-case research. Buildings designed to be lower than 10m experience a greater effectiveness to green roofs high potential to mitigate heat island (Santamouris, 2014); thus, the use-case office building has been selected accordingly, as its height qualifies it as a low-rise building under the 10m benchmark. The UHI effect is mitigated through green roof implementation, air quality purification, and the corresponding decrease in outdoor and indoor temperatures.

Data findings have reported that the SGR lowers the indoor temperatures and heat flux in the office building use-case. SGRs efficiency is assessed by the design, development, and implementation in Qatar’s hot arid region to find a balanced solution between energy consumption and users’ thermal comfort. An effective SGR comprises a native selection of plants, appropriate growing medium, large LAI, relatively tall plants, and a smart irrigation system. When these factors are in optimal capacity, a well-vegetated and well-maintained SGR could effectively block heat from entering a building compared to a bare concrete roof. SGR plant coverage provides insulation, thus, reducing cooling costs. Implementing an SGR as a component of the building envelope strategizes to (1) increase shading; (2) increase internal building heat loss through evaporation by plants; (3) resist heat transfer through thermal mass; (4) use of vegetation to achieve a cooling effect; and (5) increase user thermal comfort (Susorova, 2013). The research has discovered an optimum SGR design as follows:

- Extensive smart green roof
- Installation technique: modular (flexibility of planters as they are modular)
- Structure is composed of the following: vegetation plant layer, growing medium, drainage layer and membrane layer, waterproofing and filter layer, and plastic pods.
- Plant types: plant selection should be in coherence with the building's location and orientation, as natural weather factors, such as wind, sun, shade, and rainfall build-ups, have a direct effect on the plant's survival. The use of differing plant types leads to substantial differences in the value of thermal insulation. Qatar has a hot arid region; thus, some suitable plants are included in Figure 152.

Figure 152. Recommended suitable native local plants for hot arid regions.

- Smart drip irrigation system: wireless irrigation IoT automation platform (IRRIOT) configured with soil moisture sensors.
- Lightweight growing medium substrate of 20cm thickness.
- The growing medium is a combination of 70% sweet soil, 15% peat moss, 10% coco peat, and 5% bi-solid organic.
- Plant parameters:
  - LAI is typically in the range of 1–5, depending on the spacing between the structure (modular plastic pod), with a 2.2 optimum.
  - Plant height is dependent on the roof type, with a 28.6cm optimum research outcome (Figure 153)

Figure 153. Optimum plant condition at 2.2 leaf area index, substrate thickness of 20cm, and 28.6cm high.

Optimal substrate and plant conditions have been selected based on the best performing building environment, with the highest decrease in indoor surface ceiling temperature and heat flux during the year. Based on the interpretation in Chapter 7, it was concluded that the DesignBuilder software tool is calibrated and thus reliable; henceforth, optimal LAI and plant height were inputted. Accordingly, the optimum plant performance values have been entered into DesignBuilder to determine the effectiveness of the SGR at optimal performance, thus, generating new year-round indoor surface ceiling temperature and heat flux. The simulation for year-round optimal parameters gave different monthly data based on the influence of climatic weather conditions; the means were taken for the environmental factors under question, as shown in Table 69.

Table 69. Simulated mean indoor surface ceiling temperature and heat flux of bare and SGRs at optimal values; LAI at 2.2, height at 28.6cm, and soil thickness at 20cm

Roof Type	Environment Parameter	Zone	Mean
Bare Roof	Indoor Surface Ceiling Temperature (°C)	1	29.49
		2	29.33
		3	29.86
	Heat Flux (W/m^2)	1	0.78
		2	2.15
		3	1.51
Smart Green Roof	Indoor Surface Ceiling Temperature (°C)	1	29.15
		2	25.51
		3	25.98
	Heat Flux (W/m^2)	1	0.30
		2	0.18
		3	0.08

Note. °C, degrees Celsius; W/m^2, watts per square meter; mean, includes March-2021, April-2021, May-2021, June-2021, July-2021, August-2021, September-2021, and October-2021, November-2021, December-2021, January-2022, and February-2022 months.

As depicted in Table 69, Zone 1 saw a reduction of 0.34°C for indoor surface ceiling temperature, zone 2 at 3.82°C, and zone 3 at 3.88°C. As for heat flux decreases, zone 1 at $0.48W/m^2$, zone 2 at $1.97W/m^2$, and zone 3 at $1.43W/m^2$. Thus, it can be concluded that with a dense LAI and tall plants, shading is increased by more canopy vegetative coverage. Thereby corresponding to a better-performing and more effective SGR system.

As for real-time, the experiment could not be repeated due to a myriad of factors. Primarily because optimal plant conditions cannot be guaranteed year-round, despite efforts to maintain the vegetation. Secondly, it is not possible to go back in time to the start of the experiment in March 2021 to experience the same weather and climatic conditions. And finally, due to a lack of time and resources, it is not feasible to carry on the research study for another year, from March 2022 to February 2023. Thus, only January 2022 and February 2022 are considered in which near-optimal LAI and plant height were observed (Table 70).

Table 70. Real-time zone 2 environmental factors of bare and smart green roofs at optimal values

Type	Environmental Factors	Units	Month	
			Jan 2022	Feb 2022
Plant characteristics	LAI	no units	2.00	2.20
	Plant height	cm	28.60	28.60
	Soil thickness	cm	20.00	20.00
Bare roof	Outdoor temperature at 1m high	°C	19.70	22.60
	Indoor ambient temperature	°C	22.24	22.65
	Indoor surface ceiling temperature	°C	22.04	22.05
	Heat flux	W/m^2	-1.10	0.89
Smart green roof	Outdoor temperature at 1m high	°C	19.56	22.47
	Indoor ambient temperature	°C	22.01	21.89
	Indoor surface ceiling temperature	°C	21.58	21.06
	Heat flux	W/m^2	-1.09	0.18

Note. Jan 2022, January 2022; Feb 2022, February 2022; cm, centimeters; ºC, degrees Celsius; and W/m^2, watts per square meter.

The reduction in these environmental factors as an effect of SGR performance compared to the bare roof in January 2022 conformed to:

- A lowering of 0.14°C outdoor temperature at 1m high
- A diminished indoor ambient temperature of 0.23°C
- A decrease of 0.46°C indoor surface ceiling temperature,

- With a -0.01 W/m^2 change in heat flux

While in February 2022, these environmental factors experienced a more significant improvement that affected energy consumption cooling system costs, and users' thermal comfort. This was a direct result of a higher LAI value of 2.2, rather than 2.0, resulting in:

- A lowering of 0.13°C outdoor temperature at 1m high
- A diminished indoor ambient temperature of 0.76°C
- A decrease of 0.99°C indoor surface ceiling temperature,
- With a 0.71W/m^2 drop in heat flux

8.3 Study Limitations

The study's limitations with respect to the SGR research by no means influenced outcomes and conclusions. These limitations are principally attributed to equipment availability and faults and simulation tool hindrances. The irrigation system was inclusive of two phases: phase 1 being the manual irrigation from 1 March 2021 to 30 April 2021 for two months, and phase 2 being the smart, sustainable drip irrigation system from 1 May 2021 to 28 February 2022 for a total of eight months. The initial concept was to implement smart irrigation throughout the entire experimental set-up; however, it began in May due to limited resources and awaiting pieces of equipment and instruments to be received. However, this limitation reaped comparative analysis benefits between manual and smart irrigation, with findings being significant in terms of a reduced amount of water volume consumption by the plants upon smart application.

The scope of the research was limited by incorrect data acquisition by the loggers and sensors resulting from weather conditions (essentially wind) or improper handling (Figure 154). These errors were promptly corrected during the monitoring period. Overall, more than 17520 data points were recorded, and upon complete data acquisition, these data were then carefully sorted, and the outliers were discarded. Further, another limitation was the ability to purchase a single soil moisture sensor; thus, only one pod had a sensor, as was due to the price of the equipment. In addition, there is missing data resulting from human error and as shown in Figure 155.

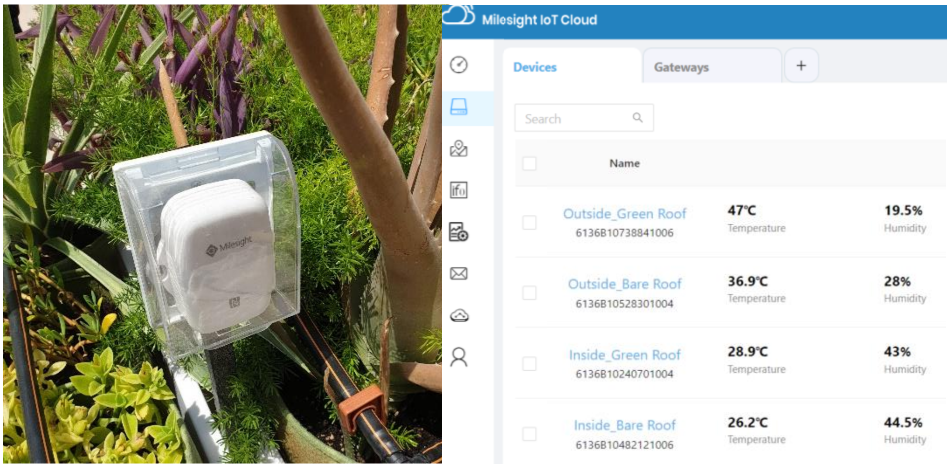


Figure 154. Incorrect data collection by loggers and sensors due to weather conditions and improper handling.

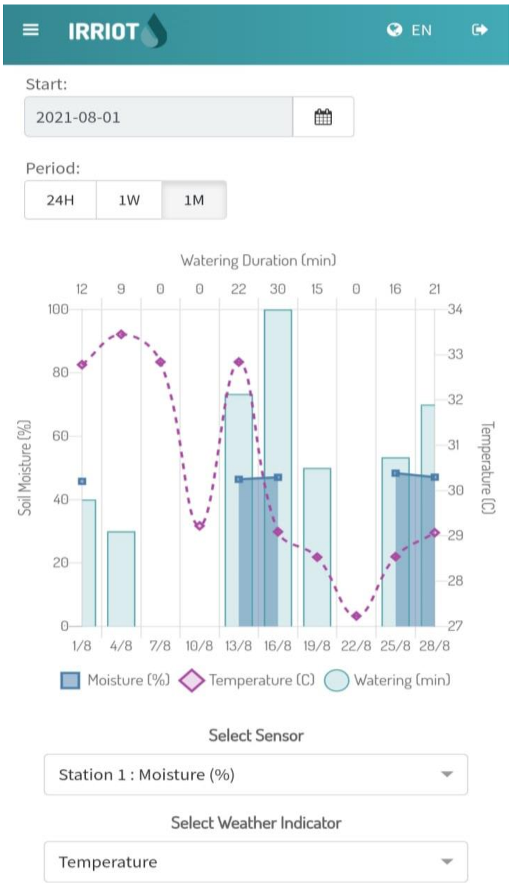


Figure 155. Missing data.

The study partly relies on computer software to model the SGR to generate simulated data on the thermal performance and energy of the building. However, the tool has other strengths that involve data generation regarding carbon sequestration, but this is not covered in the study (Abdin et al., 2018). The scope of the research incorporated data acquisition on plant performance parameters, plant color, and soil temperature for real-time study. These parameters, however, were not considered by the DesignBuilder software to calculate their parametric influence on temperatures and heat flux.

In addition, the simulation tool has limited capabilities in calculating plant performance. Thus, the values were inputted per month for LAI, height, and soil moisture according to the real-time data. In saying this, color is a variable in DesignBuilder; however, color data is used for display purposes when the texture is unavailable; it is not used in any of the calculations. DesignBuilder lacks the ability to mimic varying plant color influences on environmental factors. With the adoption and integration of a universal color classification system specific to plants, DesignBuilder will be able to generate simulated data on building thermal performance pertaining to fluctuations in plant color.

DesignBuilder cannot simulate outdoor surface temperature based on the different zones (1, 2, and 3). It is only able to simulate outdoor relative temperature. Thus, only real-time data was used to analyze outdoor temperature at 1m high for bare and green roofs. Additionally, because the smart green model was entered in DesignBuilder, the tool could not address the level of green roof coverage per zone. Lastly, the weather data file embedded in DesignBuilder for Qatar was for 2015 (Figure 156). A more recent weather file version for Doha's location could not be obtained.

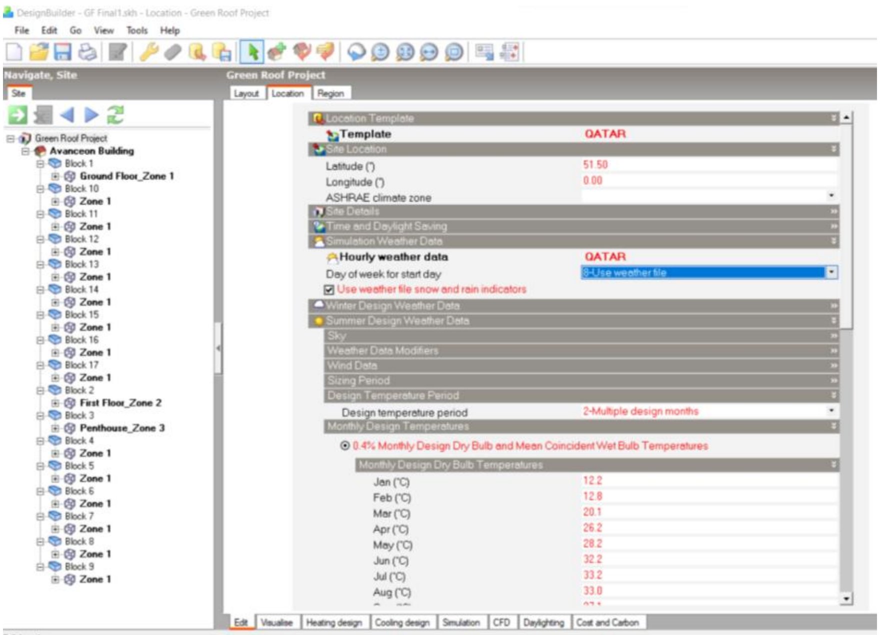


Figure 156. Weather data file embedded for Qatar 2015 in DesignBuilder.

8.4 Future Research Studies

The scope of the study focused on examining a balance between energy saving and thermal comfort through the design, development, and implementation of an SGR. However, sustainable means of water supply for irrigation were not covered. Therefore, it is vital that water-saving systems be designed to be implemented. Future directions for SGR design could encompass irrigation supply through greywater use. Another system could involve the use of air conditioning water condensation, while a third option would be integrating a solar panel add-on system.

Further research into calculations around the volume of greywater needed to suffice irrigation needs must depend on the size and plant requirements of the SGR. Greywater includes wastewater produced from the bathroom sinks and laundry. Suppose greywater is to be thought of as an alternative to potable water for irrigation of plants. In that case, a plumbing line must be installed during the initial construction of the building to separate greywater from sewage water. Taking the office building use-case as an example, the greywater resulting from the building must first be treated and then used to irrigate the SGR. An analysis of the cost of greywater treatment systems must be covered to assess this approach's eligibility for irrigation activities.

With a hot arid climate, water is a constant concern. Another measure to enhance the sustainability of the SGR is the accessibility of available condensate water from the air conditioning cooling systems. The air conditioning condensation from the office building to the rooftop’s SGR is allocated to serve irrigation purposes. Connection from the building’s cooling air conditioning system to the irrigation system of the SGR is a valid and plausible feat. This is regarding the notion that condensation does not necessitate a treatment process, as AC condensate water forms when the system cools warm air, which then exits through a drain into the sewer. Future research for SGR design would entail designing and developing a method to route the drain into the smart irrigation system to water the plants and then testing the effectiveness of this condensate water against combatting heat flux.

Another water-saving initiative currently being heavily researched in Saudi Arabia is integrating a solar panel add-on system to harvest water sustainably without electricity use (Page, 2022). This is done by exploiting day-night temperature changes. At night, water vapor from the desert air is absorbed by a hydrogel placed in a metal box under each panel. During the day, with a closed container, the sun causes the water to evaporate, increasing humidity in the box and causing water condensation, which can then be drained. This is yet another means to irrigate the SGR sustainably. Further solar panel additions may be able to operate the mechanics and pumping system for the drained water to enter the smart irrigation system of the green roof. The use-case concluded that three times watering during the day suffices, so this approach would be a duality of sustainable water supply working alongside sustainable energy supply.

Future work should investigate botanical information of native Qatar plants. This can be achieved by conducting research that categorizes Qatar’s native desert plants, their irrigation requirements, and their thermal behaviors by their association with leaf texture, leaf thickness, foliage density, and leaf color lightness (Friedman, 2017). Understanding the effects of native plants and their cooling performance will help develop strategies to suit the vegetation needs of the SGR system in a hot arid climate.

Simulation studies have been investigated to a significant extent regarding green roofs. This study concludes that the DesignBuilder simulation model calibrated in this work can be used during the design stages of a new building. Taking scale and environment into consideration, the simulation tool will evaluate the performance of the SGR operating under various climatic conditions. Henceforth, future parametric analysis may utilize this simulation model for research purposes, alongside experimental research.

The literature concerning the smart aspect of green roofs is unavailable. Nevertheless, this dissertation detected a positive influence on multiple fronts of a smart application to the irrigation system. On another note, not many simulation tools are able to conduct a green roof energy analysis; therefore, it would be interesting to evaluate and compare different software with respect to green roof energy performance. It would also be beneficial to develop new software algorithms without restricting the number of subsets. Another area that needs research is using various simulation tools to determine which simulates the behavior of SGRs more effectively and accurately. A comparative analysis of differing software will highlight which program or simulation engine is best for certain investigations.

Moreover, many variables, such as the materials, physical structure, substrate type, plant species, depth, composition, and moisture level, affect an SGR system's performance. However, these variables are not examined individually while maintaining the other aspects constant. Thus, future real-time studies can be designed to explore the effect of these variables separately and create a plant palette optimal for various greenery systems in Qatar. However, it is essential to note that the parametric study involved altering the SGR's plant parameters, either LAI and/or plant height, for each simulation run to understand its individual and combined direct effect on the building’s energy loads and thermal behavior.

An additional study involving two neighboring office buildings, one without any manipulation, a bare roof, the other implemented with an SGR over the entire building roof area, to assess the full effect of its application. The two buildings must be similar in height and be adjacent to experience the same climate and weather conditions. Future research could include considering other factors such as different building types according to their function, roof type (flat, sloped, shaded, non-shaded, etc.), and various other climate zones that could be investigated.

Further investigations could be conducted over a longer duration (more than a year), effectively increasing the sample size and record and assess more environmental factors. For instance, to study the outcome of the SGR on the environment, including carbon dioxide and urban heat island effect. Studies have found that carbon dioxide is reduced directly due to reduced energy consumption and air condition cooling use (Alabadla, 2013).

In addition, exploring different green roof design options with differing soil depths, ranging between 10-90cm thick, and plant characteristics such as types, height, and LAI. As the substrate/soil layer is crucial to the roof's cooling, a detailed analysis of the substrate layer would help maximize the SGR advantage. The substrate layer supports and maintains the vegetation, and the evaporation of water from this layer aids in achieving ambient cooling (Shao et al., 2021). It may also be beneficial to establish substrate type and depth that would be resistant to harsh climate conditions.

With the COVID-19 pandemic and extended lockdown affecting all lives, SGRs can be transformed into roof gardens. This social and behavioral dimension could be inserted and reap many fundamental advantages. Families would experience a balance in a safe, aesthetic, green space that allows for human interaction and reconnection with nature. Revisiting and socially engineering green spaces to ensure urban agriculture, social gatherings, shaded areas, and a place for families to get together should not be a discarded concept.

With these exhaustive investigations, the viability of an SGR in a particular climate would be irrefutably proven. The list of experiments and simulations would assist professionals, urban planners, designers, architects, and engineers in optimizing their information and making the best decisions. A more efficient, smart, and sustainable future with energy-saving capabilities would be witnessed, thus, having green cities match building design with their environment.

In conclusion, upon scientific literature evidence and with the presented results, strong and robust arguments can be made for changing cityscapes. The State of Qatar may incorporate SGRs into its green building initiative and decree new laws, as part of GSAS Design and Build 2019 and Ministry of Municipality and Environment (MME). A mandate incorporating SGRs in the building code would be a remarkable step towards sustainable cities and infrastructure. Ultimately, the building design would be shaped to maximize the roof area for SGR implementation.

PART 3 CONCLUSION

This thesis has enabled to show the study of a smart green roof and explain its effectiveness in mitigating heat, increasing users' thermal comfort, and enhancing buildings energy performance. Careful and suitable design of an SGR is a feature to the situated climatic and environmental conditions. The meticulous development of SGRs is influenced by its components, inclusive of the smart irrigation system and technology. As for SGR implementation, the climate, and geographic aspects, combined with the SGR's components and properties, interchangeably influence the deciding factors accounting for implementation.

The research develops design recommendations that can be adapted and implemented in hot arid regions. Through thorough use-case monitoring, the design, development, and implementation of smart green roofs have been achieved in hot arid climates in Qatar. Exploration of a self-serving sustainable SGR is discussed amidst future research directions.

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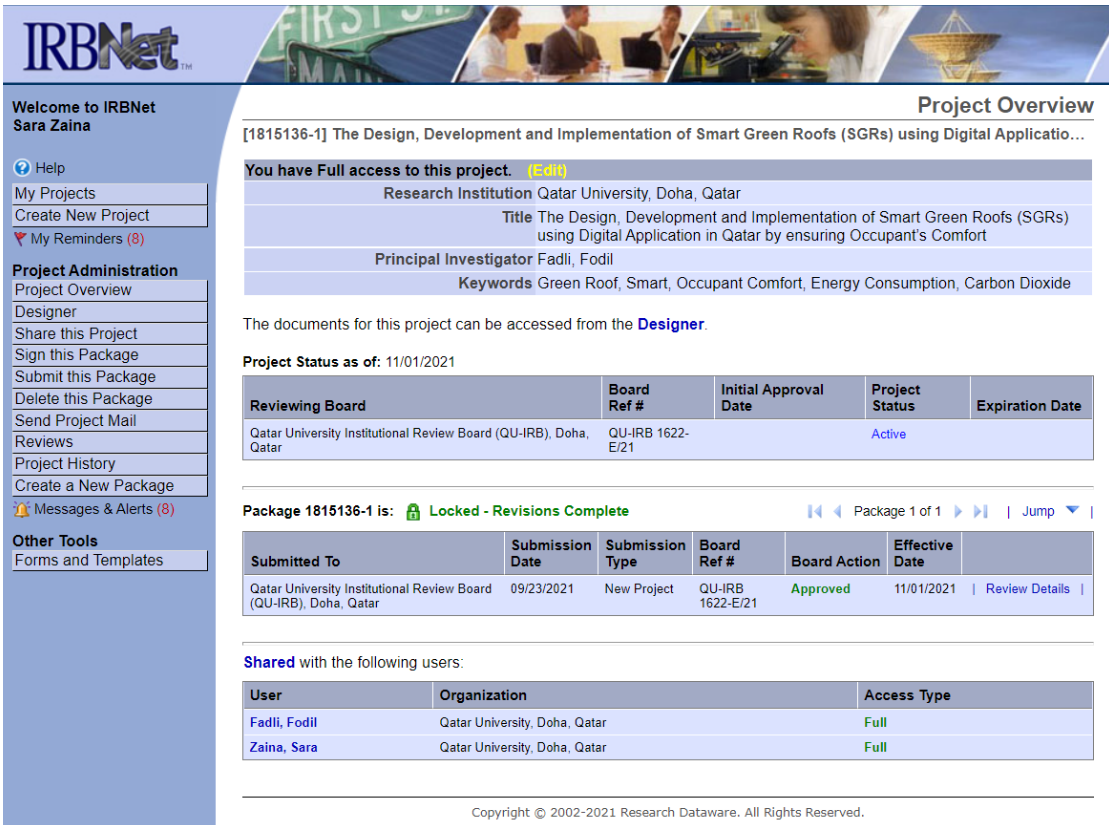
APPENDIX

Appendix A: Approval from IRB



IRBNet

Welcome to IRBNet
Sara Zaina

Help
My Projects
Create New Project
My Reminders (8)

Project Administration
Project Overview
Designer
Share this Project
Sign this Package
Submit this Package
Delete this Package
Send Project Mail
Reviews
Project History
Create a New Package
Messages & Alerts (8)

Other Tools
Forms and Templates

Project Overview

[1815136-1] The Design, Development and Implementation of Smart Green Roofs (SGRs) using Digital Applicatio...

You have Full access to this project. (Edit)	
Research Institution	Qatar University, Doha, Qatar
Title	The Design, Development and Implementation of Smart Green Roofs (SGRs) using Digital Application in Qatar by ensuring Occupant's Comfort
Principal Investigator	Fadli, Fodil
Keywords	Green Roof, Smart, Occupant Comfort, Energy Consumption, Carbon Dioxide

The documents for this project can be accessed from the **Designer**.

Project Status as of: 11/01/2021

Reviewing Board	Board Ref #	Initial Approval Date	Project Status	Expiration Date
Qatar University Institutional Review Board (QU-IRB), Doha, Qatar	QU-IRB 1622-E/21		Active	

Package 1815136-1 is: Locked - Revisions Complete   Package 1 of 1 | Jump |

Submitted To	Submission Date	Submission Type	Board Ref #	Board Action	Effective Date	
Qatar University Institutional Review Board (QU-IRB), Doha, Qatar	09/23/2021	New Project	QU-IRB 1622-E/21	Approved	11/01/2021	Review Details

Shared with the following users:

User	Organization	Access Type
Fadli, Fodil	Qatar University, Doha, Qatar	Full
Zaina, Sara	Qatar University, Doha, Qatar	Full

Appendix B: Questionnaire

User Perception and Comfort

The study is approved by the Qatar University Institutional Review Board with the approval number 1815136-1. This survey is being undertaken as part of a PhD research project on the Design, Development and Implementation of Smart Green Roofs using Digital Application in Qatar ensuring occupant's comfort, health, and wellbeing". It aims to minimize energy consumption, enhance occupants' thermal comfort, and reduce carbon dioxide. Moreover, this survey focuses on building users in Doha. The survey uses human perceptions to ensure user comfort on the indoor environment quality of the building that will be simulated and modelled by implementing a green roof system.

Kindly be informed that all information collected through this survey will be treated as strictly confidential and will be used only for research purposes. No information about the individuals who have participated in this survey will be disclosed to anyone at any time. (This questionnaire has been tested and will require 5 minutes of your time). Please note that participation is voluntary, you can skip any question or withdraw at any time.

Section A: Background Information

1. Gender

Mark only one oval.

- Male
- Female

2. Age

Mark only one oval.

- 18 - 20
- 21 - 30
- 31 - 40
- 41 - 50
- 51 - 60
- Over 60 years

3. Occupation (in the building)

Mark only one oval.

- Office Worker
- Maintenance Engineer
- Other: ____________________

Section B: General Room Perception and User Comfort

4. Level Number

Mark only one oval.

- Ground
- Level1
- Penthouse

5. Indicate your comfort level of 9temperature in the work area of the building?

Legend: 1. very uncomfortable, 2. uncomfortable, 3. neutral, 4. comfortable, 5. very comfortable

Mark only one oval.

	1	2	3	4	5	
Very uncomfortable						Very comfortable

6. In terms of wellbeing, what factors would you like to change in the building?

Check all that apply.

- [ ] Air temperature
- [ ] Ventilation
- [ ] Air Conditioning
- [ ] Lighting
- [ ] Daylight
- [ ] Access to Good Views
- [ ] Acoustics
- [ ] Spatial Arrangements

7. If you feel that there is an indoor environment quality problem, does the problem occur more frequently during specific seasons of the year?

Mark only one oval.

- ( ) Yes
- ( ) No
- ( ) Don't know
- ( ) Not applicable

8. If you answered yes to the question above, rank each season from one to five which can be associated with indoor environment quality.

Legend: 1. Very un-likely, 2. un-likely, 3. neutral, 4. likely, 5. very likely

Mark only one oval per row.

	1	2	3	4	5
Summer Season	( )	( )	( )	( )	( )
Winter Season	( )	( )	( )	( )	( )

9. When do indoor environment quality problems seem to be most notable?

Mark only one oval.

- Morning
- Afternoon
- All day
- Not applicable

10. Indicate whether your room has an Air Conditioning, if yes please tick the box that best describes the time of the day that you use the Air Conditioning.

Mark only one oval.

- No Air Conditioning
- Never
- Hardly ever
- AM
- PM
- Most of the day

Section C: Adaptive Strategies

11. Describe below steps that you may have taken to minimize any physical discomfort at work over the summer or winter season?

12. Describe any changes to your working space that would improve your comfort at work during the summer or winter season?

____

____

____

____

____

Section D: Green Roofs

13. How familiar are you with green roofs?

Mark only one oval.

	1	2	3	4	5	
Not at all	◯	◯	◯	◯	◯	Extremely

14. In your opinion, what are the reasons of having green roofs in the building?

Mark only one oval per row.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Increase aesthetics					
Reduce ambient temperature					
Reduce relative humidity					
Reduce noise					
Reduce energy consumption of buildings					
Improve outdoor air quality					
Improve indoor air quality and comfort					
Improve public health					
Help sustain wildlife and biodiversity					

Appendix C: Interview

Green Roofs

The study is approved by the Qatar University Institutional Review Board with the approval number 1815136-1. This survey is being undertaken as part of a PhD research project on the Design, Development and Implementation of Smart Green Roofs using Digital Application in Qatar ensuring occupant's comfort, health, and wellbeing". It aims to minimize energy consumption, enhance occupants' thermal comfort, and reduce carbon dioxide. The aim of this survey is to examine the knowledge and awareness level; and capture perceptions and barriers of people with respect to green roofs.

Kindly be informed that all information collected through this survey will be treated as strictly confidential and will be used only for research purposes. No information about the individuals who have participated in this survey will be disclosed to anyone at any time. (This questionnaire has been tested and will require 5 minutes of your time). Please note that participation is voluntary, you can skip any question or withdraw at any time.

Profile of the Respondents

1. Gender

Mark only one oval.

- Male
- Female

2. Profession

Mark only one oval.

- Designer/architect
- Engineer
- Project Manager
- Faculty
- Student
- Other: ______________________

Green Roofs

Legend: 1 - not at all, 2 - slightly, 3 - neutral, 4 - moderately, 5 - extremely

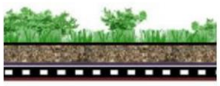
3. How familiar are you with green roofs?

Mark only one oval.

	1	2	3	4	5	
Not at all	⬭	⬭	⬭	⬭	⬭	Extremely

4. What type/s of green roof design are you familiar with, if any? (select all that apply)

Check all that apply.



☐ Extensive

☐ Semi-Intensive

☐ Intensive

5. In your opinion, what might green roofs be able to achieve?

Mark only one oval per row.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Increase aesthetics	⬭	⬭	⬭	⬭	⬭
Reduce temperature	⬭	⬭	⬭	⬭	⬭
Reduce humidity	⬭	⬭	⬭	⬭	⬭
Reduce noise	⬭	⬭	⬭	⬭	⬭
Improve energy efficiency of buildings	⬭	⬭	⬭	⬭	⬭
Improve rainwater runoff problems	⬭	⬭	⬭	⬭	⬭
Improve outdoor air quality	⬭	⬭	⬭	⬭	⬭
Enhance indoor air quality and comfort	⬭	⬭	⬭	⬭	⬭
Improve public health	⬭	⬭	⬭	⬭	⬭
Help increase wildlife and biodiversity	⬭	⬭	⬭	⬭	⬭
Add value/marketability to the property	⬭	⬭	⬭	⬭	⬭
Add unnecessary cost without much benefit	⬭	⬭	⬭	⬭	⬭

6. What are the difficulties or constraints in implementing green roofs? (select all that apply)

Check all that apply.

- [ ] Lack of knowledge
- [ ] Lack of owner/client's interest
- [ ] Additional design, construction and maintenance cost
- [ ] Lack of awareness about sustainable environment
- [ ] Increase in structural load
- [ ] Not included in the building code
- [ ] Difficulties in design and construction (technical)
- [ ] Regular maintenance
- [ ] Lack of skilled manpower
- [ ] Climatic reasons
- [ ] Legislation reasons (no place for the water tank, satellite dish, etc.)
- [ ] Cultural reasons (ground close to nature)
- [ ] Other: ______________________

7. What are the measures that can enhance the implementation of green roof systems, for new and/or existing buildings? (select all that apply)

Check all that apply.

- [ ] Incentives from government to developers and owners
- [ ] Increase awareness about sustainable environment
- [ ] Percentage of green space should be mandatory for property development project
- [ ] Bonus to developers (e.g., reduced government fee) who construct certain green roof areas
- [ ] Green roof regulations to improve rainwater runoff problem
- [ ] Include green roof in the educational curricula for anyone entering the construction industry
- [ ] New building codes for developers/contractors
- [ ] Other: ______________________

Additional Questions

Legend: 1 - not at all, 2 - slightly, 3 - neutral, 4 - moderately, 5 - extremely

8. In some countries green-roofs are utilized for other purposes like recreational area, urban farming etc. In your opinion, are rooftops neglected spaces in buildings in Qatar?

Mark only one oval.

	1	2	3	4	5	
Not at all	◯	◯	◯	◯	◯	Extremely

9. In your opinion in terms of adaptive strategies, how would you change indoor working space that would improve the occupants comfort in the building during the summer or winter season?

____