Green Roofs and Green Walls as Heat Stress Mitigation Strategies for New Delhi, India

Master Thesis

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Abstract

New Delhi, India's urban environment is grappling with escalating challenges posed by rising heat stress, exacerbated by urban heat islands, rapid urbanization, and deteriorating air quality. This master's thesis underscores the urgent imperative of implementing green roofs and green walls as nature-based solutions to combat these pressing issues. Green Roofs and Green Walls are sustainable building elements that incorporate living vegetation to enhance environmental benefits and aesthetic appeal.

With climate change projections indicating an increase in the frequency and duration of heat waves, posing grave risks to human health and the environment, the adoption of these solutions has become paramount.

At the building scale, these solutions not only reduce energy consumption, and enhance insulation properties which ensures thermal comfort for residents, but also foster microclimates that lower air and surface temperatures, manage stormwater, boost biodiversity, purify the air, enhance well-being, improve aesthetics, mitigate noise pollution, and store rainwater for future use. On a citywide scale, the adoption of green roofs and green walls contributes to the mitigation of the urban heat island effect, maintaining clean air in the city, reducing noise pollution, combatting smog, promoting sustainability, and enabling cities to be resilient and future-ready by mitigating and adapting to the effects of climate change.

This thesis takes a comprehensive approach by meticulously examining various critical factors that underpin the successful adaptation of green roofs and green walls to the unique climatic conditions of New Delhi, India. It delves into the intricacies of substrate selection, plant species suitability, water dependency, and other essential considerations, all supported by scientific studies. By encompassing both small-scale and large-scale factors, this research aims to bridge the gap of uncertainty surrounding the integration of green infrastructure in the cities. The overarching aim of this thesis is to offer practical insights and actionable knowledge to a diverse audience, including architects, designers, urban planners, developers, and other stakeholders. Through an evidence-based approach, this research seeks to empower these professionals with the tools and information needed to confidently integrate green roofs and green walls into their future projects. This study examines how the deployment of green roofs and green walls can alleviate heat stress in New Delhi. It incorporates the proposal of a design case tailored to the specific climatic conditions and urban context of New Delhi.

This study aspires to be a catalyst for the widespread adoption of green technologies, fostering sustainable urban development and addressing the pressing challenges of heat stress, urbanization, and pollution in the city. Furthermore, the implementation of these nature-based solutions aligns with the broader goal of advancing sustainable living practices and reducing the carbon footprint of buildings. This research underscores the transformative potential of green roofs and green walls in reshaping the urban landscape of New Delhi, making it healthier, greener, and more sustainable for its residents while offering valuable insights for cities worldwide facing similar challenges.

Abstract

Keywords: *green roof, green wall, living wall, vertical greenery, vertical garden, terrace garden, building greenery system, guidelines, plant selection, plant survival, substrate selection, blue green roof, heat mitigation, air purification, biodiversity, energy reduction, reduced cooling loads, ecosystem services, technical adaptation, climate change, global warming, well-being, green building certification, biophilic design, nature-based solutions, urban heat island, aesthetics, sustainable infrastructure*.

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List of Acronyms

APTI - Air Pollution Tolerance Index

ART- Attention Restoration Theory

BGR- Blue Green Roof

BGS – Building Greenery Systems

BREEAM- Building Research Establishment Environmental Assessment Method

CSIRO- Commonwealth Scientific and Industrial Research Organization

EPDM- Ethylene Propylene Diene (Monomer)

FLL - Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V.

GF – Green Facade

GFS- Green Facade System

GR- Green Roof

GRIHA- Green Rating for Integrated Habitat Assessment

GW- Green Wall

GW_C – Green Wall (Climber plant or Trellis type)

GW_P – Green Wall (Panel fitted)

HVAC- Heating, Ventilation and Air-Conditioning

IGBC - Indian Green Building Council

IPCC- Intergovernmental Panel on Climate Change

LAI - Leaf Area Index

LEED- Leadership in Energy and Environmental Design

MWh- Megawatt hour

PV- Photovoltaic

PVC- Polyvinyl Chloride

PV-GR - Photovoltaic on Green Roof

RH- Relative Humidity

RWC- Relative Water Content

SRT- Stress Recovery Theory

TERI- The Energy and Resources Institute

UAE- United Arab Emirates

UHI- Urban Heat Island

VGS- Vertical Greenery Systems

VWC - Volumetric Water Content

Chapter 1 Research Framework

1.1 Problem Statement

New Delhi has a semi-arid climate (Köppen climate classification BSh) with an overlap of humid subtropical (Köppen climate classification Cwa) from June to August as an influence of the monsoon. The onset of summer is characterized by limited rainfall and high temperatures, and the challenges of water scarcity and extreme heat intensify the need for effective green infrastructure.

The origin of Green Roofs can be traced back to 600 BC in Ancient Mesopotamia when it was used to mitigate the hot climatic conditions as recreational space or to express the social status of the owner. Much later, the evidence depicts that turf-pitched roofs were also used in cold climates such as in Scandinavian countries around 800 AD for thermal insulation (Abass et al., 2020). In the 1800s, Germany laid the foundation for modern-day green roofing systems, and later, sophisticated irrigation systems and roof ingress protection followed (Nancy, 2020).

The implementation of green roofs and green walls have gained substantial attention in recent decades as sustainable solutions, especially in urban built environments due to their properties like stormwater retention and urban heat island mitigation in several countries in Europe, and Asia such as Germany and Singapore. However, this adaptation to the Indian subcontinent is underway but has its own set of challenges. Green walls are widely used in the Indian subcontinent majorly because of their aesthetic value. However, their effectiveness and suitability in terms of heat stress mitigation in hot regions remain unaddressed.

The suitability and performance of GRs and GWs in terms of water retention, reducing urban heat islands, and improving air quality under these specific climatic conditions require thorough investigation. The problem at hand is the need for more comprehensive research and knowledge on specific design considerations, plant selection, substrate suitability, and maintenance practices. Implementation of urban greenery in such a complex climatic region as New Delhi remains hesitant, hinting towards a pressing problem, or rather a solution in sustainable urban development. Drawing insights from the city-state of Singapore, which faces a similar high population density, a successful model has been established to address this issue. By proactively integrating elevated parks and gardens in the buildings through robust governmental support, Singapore has effectively mitigated heat islands and expanded green spaces, serving as a valuable precedent for New Delhi's quest for sustainable urban solutions (Newman, 2014).

With the presence of these unique challenges and opportunities in this climate type, urban planners, architects, and policymakers struggle to integrate green infrastructure prominently into their design. This study aims to address this gap in knowledge by investigating the performance, feasibility, and appropriate design considerations for green roofs and green walls in the semi-arid and humid subtropical region which is the Indian capital, New Delhi. New Delhi was selected as the focal city for this thesis study due to its representative portrayal of the prevailing hot climatic conditions in a majority of North India's states. Additionally, the city's designation as a tier 1 urban center enhances the viability of implementing pilot projects with a high probability of successful execution, while its notable air pollution levels underscore the urgency and relevance of investigating sustainable urban development strategies.

1.2 Vision

This thesis aims to explore the possibilities of increasing the efficiency of GR and GW systems through available evidence-based research in similar climatic conditions, clubbed with the experiences of experts already indulged in the particular field. The result of this research would then be the development of guidelines for the adaptability of suitable greenery systems based on the factors on which the efficacy lies. It has been further explored in the thesis. By providing evidence-based recommendations, this research intends to contribute to sustainable urban development practices, improving environmental quality, biodiversity, and human well-being, supporting the energy transition, and enhancing the resilience of the urban areas in these challenging climatic zones.

1.3 Research Questions

According to the problem stated above, the main objective of the research is to contribute to the adaptability of green roofs and green walls with a main focus on heat stress mitigation in the city of New Delhi nonetheless portraying the secondary and tertiary services delivered by the system.

- **How can Green Roofs and Green Walls help in the reduction of heat stress in New Delhi?**
- **How can Green Roofs and Green Walls be adapted to New Delhi's climate? What technical adaptations might be required for the implementation of these systems?**
- **What ecosystem services can these products provide to the surrounding environment?**

1.4 Relevance

Significant and swift alterations have taken place in the Earth's atmosphere, oceans, cryosphere (frozen areas), and biosphere (living ecosystems). The influence of human-induced climate change is readily evident, with noticeable effects on various weather and climate extremes occurring worldwide. As a consequence, these changes have resulted in widespread negative consequences, causing significant harm and damage to both the environment and human populations. IPCC in its annual 6th Synthesis Report in 2023, published that it is likely that global warming will exceed 1.5°C during the 21st century and it is already hard to restrict the warming below 2°C. The probability of abrupt and potentially irreversible changes escalates as global warming levels rise. There is a rapidly closing window of opportunity to secure a liveable and sustainable future for all. Taking decisive, immediate, and long-lasting steps toward mitigating climate change and expediting the execution of adaptation strategies within this decade would lead to a decrease in anticipated losses and damages for both humans and ecosystems. Conversely, postponing these mitigation and adaptation efforts would result in the establishment of high-emission infrastructure, intensifying the risk of stranded assets and cost overruns, diminishing feasibility, and ultimately increasing the magnitude of losses and damages (IPCC, 2023). Implementation of Building Greenery Systems (BGS) would bring about numerous additional advantages, particularly in terms of improved air quality and public health. The transfer of concerning knowledge to the region is highly pertinent to the local climatic conditions, characterized by scorching temperatures and sporadic heavy rainfall. By offering natural insulation and shading, these green infrastructure solutions can alleviate heat stress, reduce energy consumption, and enhance urban resilience. Moreover, they help manage rainwater, combat air pollution, and promote biodiversity, addressing critical environmental and health concerns. Additionally, the aesthetic appeal of green spaces contributes to overall urban well-being. This research can enlighten sound policy decisions, fostering sustainable urban development and climate resilience in New Delhi, ultimately improving the quality of life for its residents while addressing critical environmental and health challenges. By promoting sustainable infrastructure and reducing the carbon footprint of buildings, BGS plays a pivotal role through enhanced carbon sequestration and lower carbon emissions in the global fight against climate change, aligning with India's commitment to carbon neutrality.

1.5 Research Methodology

The graphic below gives a simplistic overview of the methodology used in this research study.

Research Framework

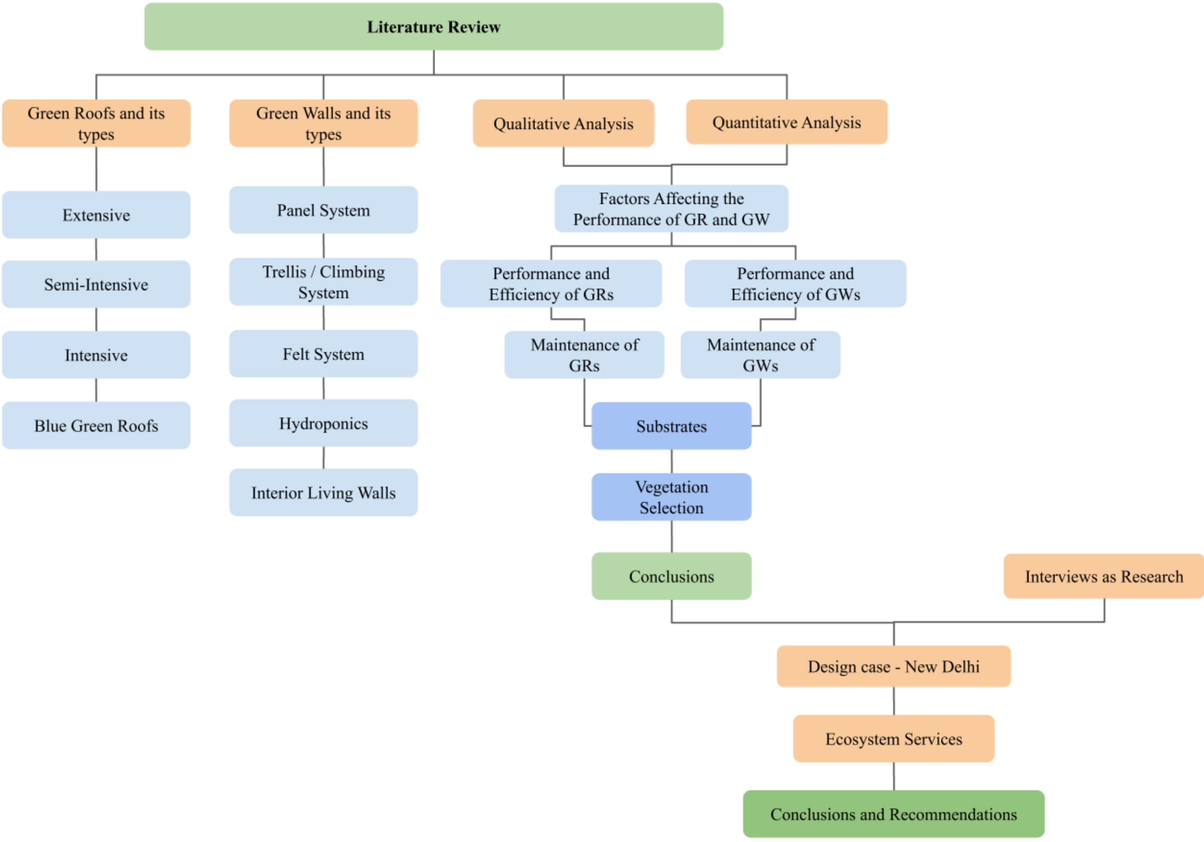

Figure 1: Descriptive flow chart explaining the structure of the thesis

The process of development of the thesis is divided into the following four phases:

Phase 1: Literature Review

Phase 2: Interviews as Research

Phase 3: Design Case

Phase 4: Conclusions and Reflections

Phase 1 consists of a thorough literature review of research papers, journals, books, and reports relevant to the research study which gives a deep insight into the technicality of the products and aids in understanding the problem statement, defining the design criteria as per the goal of the research questions. The review includes a mix of qualitative and quantitative analysis wherein the research material studied is majorly extracted from the SCOPUS database followed by Google Scholar and from some stand-alone publishing platforms. Roughly 200 research papers were screened and selected based on similar climatic conditions where the experiments were performed, methodology of experimentation, research criteria, outcomes, and relevance. Following this, about 44 scientific studies were thoroughly examined, and the results were compared with control conditions; surfacing the patterns observed among various studies.

This gave rise to five sub-categories of the obtained results to maintain coherence and clarity; namely,

- Factors Affecting the Performance and Efficiency of GRs and GWs
- Performance Evaluation
- Maintenance Criteria
- Dependence and Specifications of Substrate
- Criteria for Vegetation Selection

As the name suggests, these sub-categories then expand their respective domains to describe the magnitude of dependency of each product from different studies compiled together which facilitates the author to narrow down the relevant factors which play significant roles in the adaptation of both products for the Indian subcontinent.

Phase 2 explores the research by a slightly uncommon method which is more practice-oriented and gives a complete overview of the ground reality of the target region. Subsequently, a SWOT analysis provides a deeper outlook of the sectors that are already strong; which require more strengthening; and the sectors that might have the highest potential along with highlighting the probable threats.

Phase 3 consists of the design case of the region, giving a real-time example of how the learnings from Phase 1 and Phase 2 can be adapted to an actual existing building, portraying the implementation of GRs and GWs with technical specifications, and selected parameters as per the suitability.

Phase 4 is the final step for the finalization of this thesis where an overview of ecosystem services with the implementation of GRs and GWs is portrayed. Conclusions concerning the whole process are then made along with the recommendations laid out for future research.

1.6 Scope

GW and GR systems are majorly studied for external applications. The internal building applications of GWs are not taken into consideration in this thesis (except brief description and ecosystem services of internal living walls). The study looks into the feasibility of GWs and GRs in the composite climate of India i.e., New Delhi. Suitability and adaptability are the main focus of the research study, therefore, only the relevant information that demands adaptation to the regional context is explored and discussed. In addition to this, there are several elements used in the construction and maintenance of such greenery systems that do not require subsequent changes. Such elements may be used in synergy with the laid guidelines in this thesis with the guidelines elaborated in the 'FLL Guidelines'. Hence, the information missing in this study is either to be referred to 'FLL Guidelines for Green Roofs', 'Vertical Greening in high-density city environments - Singapore' or perhaps requires further research. Moreover, the possibility of using treated greywater for artificial irrigation of GRs and GWs exists and undoubtedly can add value to the products' implementation; however, this particular aspect exceeds the set boundaries and is, therefore, not explored in this thesis.

Chapter 2 Literature Review

2.1 What is Biophilic Design?

The term *biophilia* simply means 'the love of nature' and comes from the ancient Greek word 'bio', meaning life, and 'philia', meaning love or fondness. Biophilic design is an innovative approach to architectural and interior design that emphasizes the inclusion and integration of nature and natural elements within the built environment. Biophilic design principles draw inspiration from the patterns, forms, processes, and materials found in nature. It goes beyond simply adding decorative plants or natural materials and aims to create a deeper connection and immersion in nature (Thermory, 2023). This may include visual and non-visual connections with nature, for instance, thermal and airflow variability, dynamic and diffused lighting, indoor and outdoor plants, etc.

Figure 2: The integration of the biophilic elements of water, vegetation, organic shapes and forms, information richness, prospect, and refuge, the patina of time, and organized complexity all contribute to this scene's powerful sense of place (Kellert & Calabrese, 2015).

The effective implementation of biophilic design should yield a diverse range of advantages spanning physical, mental, and behavioral aspects. Physically, this encompasses improved physical fitness, reduced blood pressure, heightened comfort and contentment, fewer symptoms of illness, and overall better health. Mentally, the benefits encompass increased satisfaction and motivation, reduced stress and anxiety, and enhanced problem-solving abilities and creativity. Furthermore, it extends to positive behavioral changes, including improved coping and mastery skills, heightened attention and concentration, better social interactions, and reduced levels of hostility and aggression.

Figure 3: Natural landscape and ecosystems in the built environment, part of biophilic design (Kellert & Calabrese, 2015).

2.2 Heat Stress and Urban Heat Island Effect

Heat Islands

The sun is exceptionally hot, resulting in the emission of substantial radiant energy, predominantly in the ultraviolet and visible parts of the energy spectrum, known as short-wave radiation. Conversely, the Earth and everything on it also emits radiant energy, but because the Earth is cooler than the sun, this radiation occurs in the lower-energy infrared portion of the spectrum, termed long-wave radiation. The atmosphere not only receives this energy from the Earth's surface but, due to its composition, emits energy both downward towards the Earth and outward into space. Typically, the atmosphere is cooler than the Earth's surface, causing the amount of downward long-wave radiation reaching the Earth to be less than the original long-wave radiation emitted from the Earth to the atmosphere (Ronald Sass, 2023). Figure 3 illustrates the standard radiation balance.

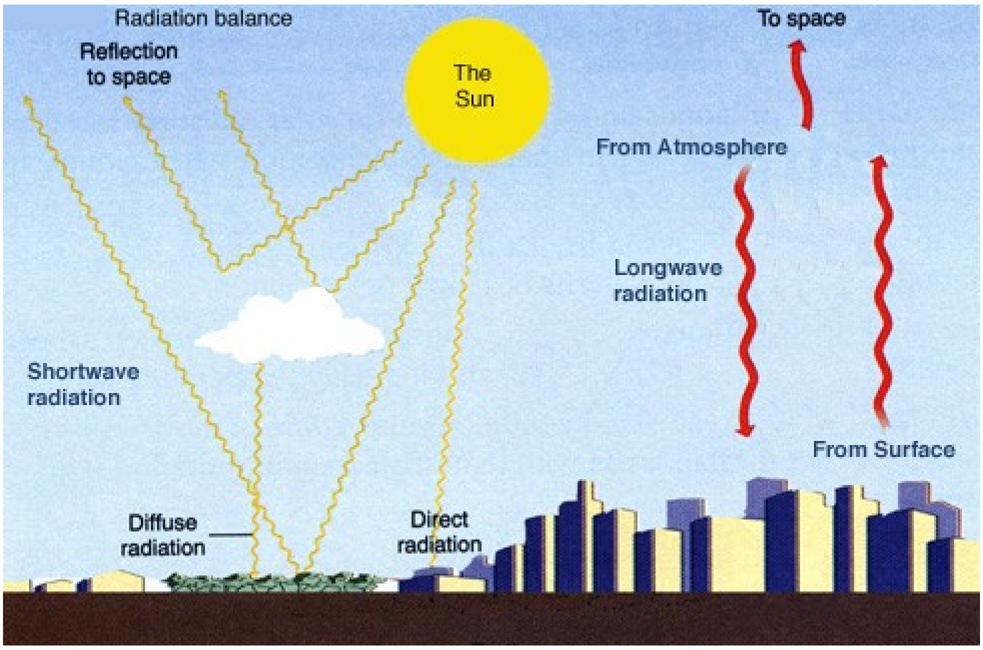

Figure 4: Radiation balance (Ronald Sass, 2023)

Man-made structures like buildings and roads tend to absorb and release solar heat remarkably and more often than natural objects such as trees, soil, forests, and water bodies. In urban environments, where these structures are densely clustered and green spaces are limited, localized areas experience substantially elevated temperatures as compared to their surroundings. The standard radiation balance is disrupted due to the use of air conditioners, heat pumps, anthropogenic heat, vehicular emissions, and heat-trapping by impervious pavements, concrete, asphalt, and other materials. Figure 5 highlights these effects in a typical city. These regions of heightened thermal conditions are referred to as 'heat islands'. Vegetation and the presence of water bodies cause evapotranspiration and absorption of shortwave radiation which lowers the effects of heat islands. With more man-made structures and a reduction in green and blue urban spaces, heat islands pop up more often and can manifest under diverse circumstances, whether it's day or night, in both small and large cities, suburban settings, northern or southern climates, and across all seasons. The effects of heat islands are experienced mostly in larger cities where the urban geometry obstructs the wind flow and changes the urban canopy (US EPA, 2014).

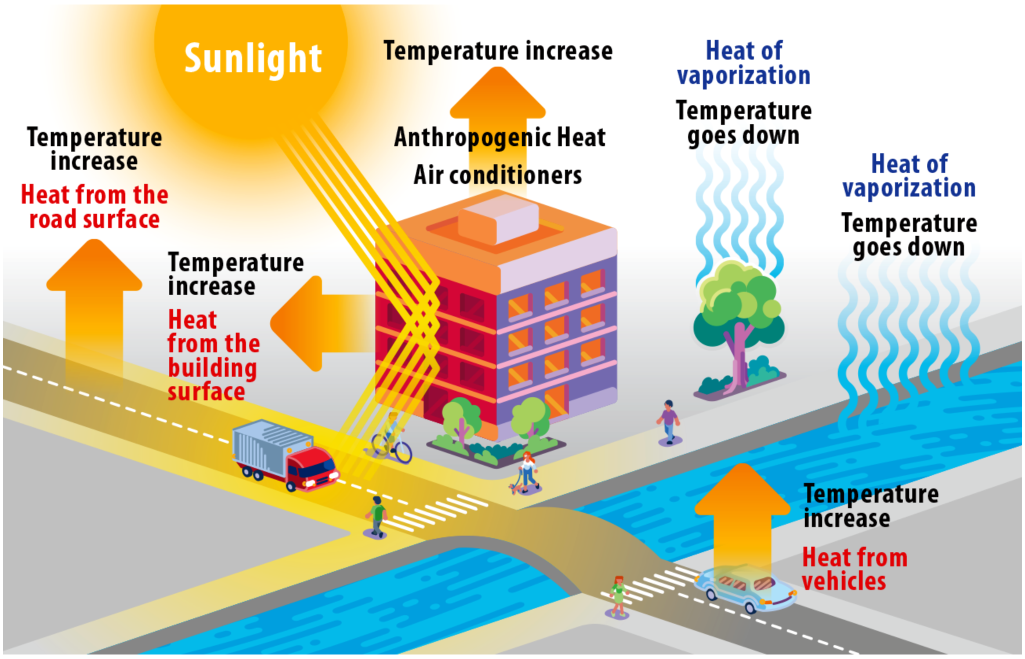

Figure 5: Urban heat island constituent sources (Pavement Technology Inc., 2023)

Effects of Urban Heat Islands

1. **Increased Energy Consumption**

   Research indicates that as air temperatures jump from 20°C to 25°C, there is a corresponding 1.5 to 2 percent surge in electricity usage, primarily driven by increased reliance on air conditioning or cooling systems. Consequently, communities grappling with Urban Heat Islands (UHI) effects experience an elevated electricity demand of approximately 5 to 10 percent or more. This heightened demand for cooling translates to increased energy consumption and subsequently higher electricity bills. Furthermore, during severe urban heat island episodes, the escalated need for air conditioning can strain electricity grids, potentially resulting in power outages and blackouts.

2. **Higher Emissions and Air Pollution Due to Increased Energy Demand**

   The intensified electricity demand stemming from UHIs places added pressure on power plants, compelling them to generate additional energy. However, these power plants typically rely on fossil fuels for energy production, leading to a notable rise in both greenhouse gas emissions and air pollutants. The primary greenhouse gases and pollutants associated with this process encompass Carbon Monoxide (CO), Carbon Dioxide (CO2), Sulfur Dioxide (SO2), Nitrogen oxide (NOx), Particulate Matter, and Mercury (Hg). This increase in emissions not only exacerbates air quality concerns but also contributes to the overall burden of greenhouse gases in the atmosphere, further fueling global climate change and its associated environmental impacts.

3. **Thermal Discomfort**

The human health impacts include heightened discomfort, fatigue, heat strokes, respiratory issues, headaches, and heat-induced cramps. UHIs can intensify heat wave impacts, leading to abnormal weather patterns that disproportionately affect vulnerable populations like the elderly, children, and those with weather-sensitive health conditions. This heightened risk during severe heat events can lead to increased mortality rates.

4. **Impacts on Weather and Climate**

   It exerts influence over various local weather phenomena, including alterations in wind patterns, the development of fog and clouds, precipitation levels, and humidity. The elevated temperatures associated with UHIs intensify the upward movement of air, potentially triggering thunderstorms and increased precipitation. Additionally, UHIs establish local low-pressure zones that draw in cooler air from nearby regions, fostering cloud formation and rainfall. Consequently, cities affected by UHIs may experience extended growing seasons for plants and crops due to these weather-induced changes.

5. **Impact on Animals**

   Elevated temperatures create inhospitable ecological conditions, constraining vital activities of organisms, including metabolism, breeding, and reproduction. Furthermore, the adverse heat can substantially diminish the accessibility of essential resources such as food, shelter, and water (Conserve Energy Future, 2016).

2.3 Green Roofs and its elements

Differing from conventional rooftop gardens, green roofs are systematically designed to counteract urbanization. The composition of green roofs involves various elements, depending on location and needs, as outlined in the figure below. To ensure that green roofs are both environmentally sound and align with client expectations in the long run, it is crucial to meticulously choose effective components for their construction.

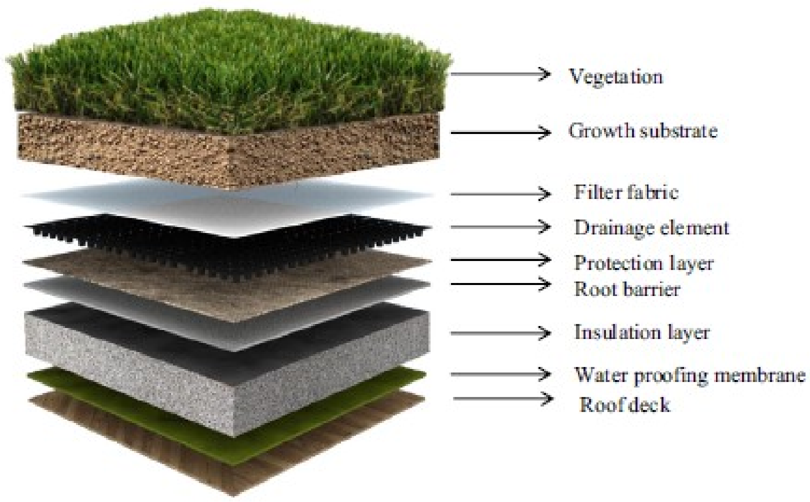

Figure 6: Schematics of a typical green roof (Vijayaraghavan, 2016).

Vegetation

Plants form the topmost layer, infusing vitality into the green roof system. The effectiveness of any green roof depends on the health of the plants. Plants contribute to the improvement of runoff quality, air quality, and thermal performance (Vijayaraghavan, 2016).

Growth substrate

The growth substrate has a direct impact on plant growth and the overall performance of green roofs. Hence, selecting a suitable substrate is paramount for the success of any green roof project. Numerous advantages of green roofs are closely linked to the characteristics of the growth substrate. These advantages incorporate enhancements in water quality, reduction of peak flows, thermal benefits, and sound insulation (Vijayaraghavan, 2016).

Filter layer

The primary role of a filter layer is to create a separation between the growth substrate and the drainage layer, effectively preventing small particles like plant debris and soil fines from infiltrating and obstructing the drainage layer beneath. Typically, geotextile fabrics are utilized for this purpose in GRs. These filter fabrics need to possess elevated tensile strength to withstand the load above. Furthermore, they should feature small pores that facilitate efficient water permeability in the normal direction while hindering the movement of soil particles into the drainage layer (Vijayaraghavan, 2016).

Drainage layer

The presence of a drainage layer is indispensable for the functionality of any GR. This layer contributes to a delicate equilibrium between air and water within the GR system. Recognizing that the majority of vegetation thrives in a well-aerated and non-waterlogged substrate, the drainage layer plays a fundamental role in evacuating surplus water from the substrate, thus guaranteeing an aerobically conducive substrate state. Moreover, the drainage layer serves to safeguard the waterproof membrane and enhance the thermal attributes of the GR. Majorly, two types of drainage layers are used nowadays:

- Drainage modular panels: Constructed from robust plastic materials (polyethylene or polystyrene), these panels incorporate compartments that can store water while enabling the expulsion of surplus water.
- Drainage granular materials: These materials possess a certain water-holding capacity alongside ample pore spaces for water storage. Examples encompass lightweight expanded clay aggregates, expanded shale, crushed brick, coarse gravel, and stone chips (Vijayaraghavan, 2016).

Root barrier

It is essential for intensive green roofs and is considered optional for extensive ones. The primary function of a root barrier is to safeguard the roof's structure from plant roots that could potentially penetrate from the upper layers of the green roof. Various commercial root barriers are accessible in the market, ranging from hard plastic sheets to metal sheets (often copper) (Vijayaraghavan, 2016).

Waterproofing layer

Ensuring a watertight seal is a prerequisite in any GR installation to prevent leaks. It's not surprising to perceive that, from an end-user standpoint, even a single water droplet leakage on the roof is often viewed as a failure of the green roof. Because of the presence of wet soil and drainage layers, the roof's moisture content remains consistently high. In the event of a leak in an operational green roof, all the layers need to be dismantled to pinpoint the source of the leak. Several options are available, including liquid-applied membranes, single-ply sheet membranes, modified bitumen sheets, and thermoplastic membranes (Vijayaraghavan, 2016).

Drains

A standard flat roof is designed to drain quickly in the worst-case event – a short intense summer storm lasting minutes, whereas a blue/green roof is designed to drain slowly – to mitigate the effects of downstream flooding that can last hours. Designing a roof drainage system to cater to both extremes is a difficult challenge. Therefore, to protect the green and blue-green roofs from flooding, in case of blockages, roof drains are used to evacuate extra water directly into storm drains. Figure 7 portrays a typical GR drain.

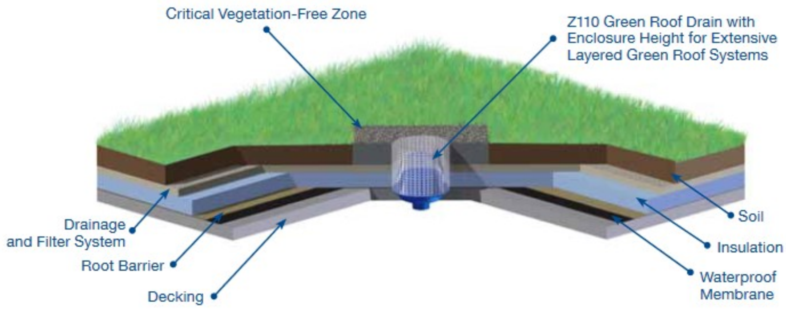

Figure 7: Schematic diagram of a green roof drain (ZURN, 2023).

Irrigation for Green Roofs

Generally, the extensive roofs are so designed that they do not require artificial irrigation and the plants can sustain through their dependence on rainwater. Although there may be cases, depending on the climatic conditions of the region, the need for artificial irrigation might exist even for extensive GRs. The irrigation for the green roofs is to be preferably from non-potable water sources to reduce the stress on freshwater resources. Stored rainwater use for GR irrigation is advocated by FLL Guidelines along with other GR societies. Partially treated greywater also has the potential to be used for irrigation of these roofs. The four main methods used in GR irrigation are:

Standing water system: This system retains a water layer at the bottom of the Green Roof. It is regulated by using a floating control device which is self-regulated and can be filled with rainfall.

Capillary system: This system is ideal to be used in shallow GRs with a substrate thickness of 200 mm or less. In this system, water is delivered to the substrate base by porous mats. The water is supplied to the roof in specific locations and then distributed by the capillary mat.

Drip and tube system: This system can be either buried in the substrate or attached to the substrate surface. Sub-irrigation system is not visible and delivers water to the roots directly which reduces water loss through evaporation.

Surface spray with sprinkler: This system sprays the water on the roof using a sprinkler system. It is undesirable as a large percentage of the water is wasted. It also encourages the rooting on the surface which makes the roots exposed to climate conditions (Satumane et al., 2018).

Types of Green Roofs

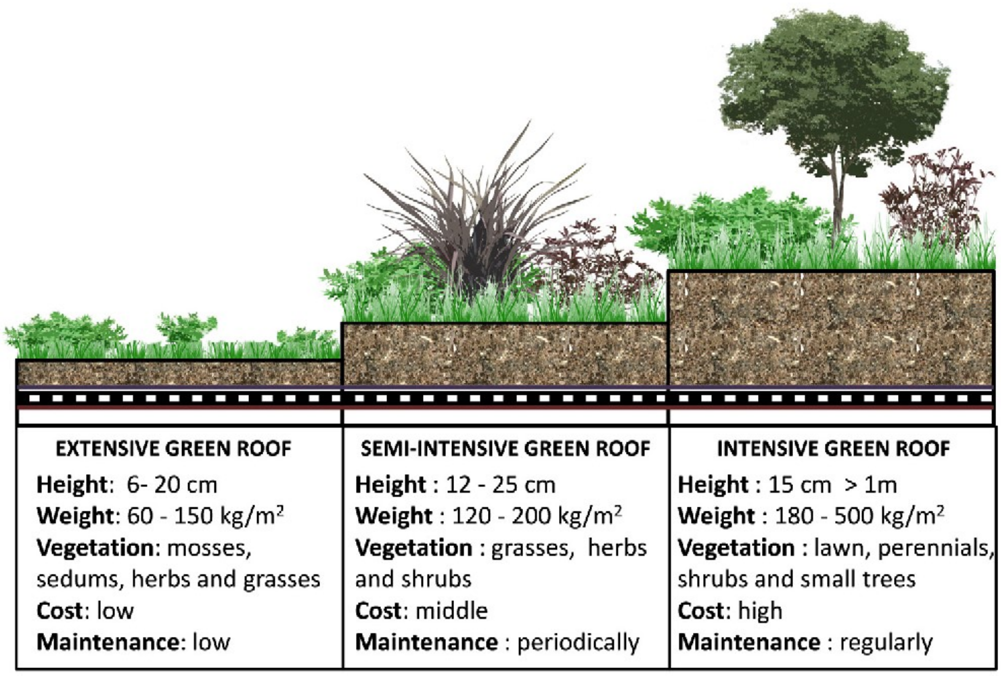

Figure 8: Extensive, Semi-intensive, and Intensive green roof comparison (Fernandez-Cañero et al., 2013).

Extensive

Extensive GRs are primarily designed for ecological landscaping purposes, emphasizing the use of moss, herbs, and grasses as their dominant vegetation. With a substrate depth ranging from 60 to 200 mm, these roofs are relatively lightweight, typically weighing around 60 to 150 kg/m^2. They offer benefits in terms of water retention, thermal insulation, and biodiversity enhancement. Extensive green roofs tend to be cost-effective in terms of installation (Livingroof.org, 2016).

Figure 9: Extensive green roof in Portugal (EFB, 2017).

Semi-Intensive

Semi-intensive GRs serve as a middle ground between ecological landscaping and garden/park-like usage. They incorporate a mix of grasses, herbs, and shrubs, making them suitable for both ecological landscaping and creating garden-like spaces. The substrate depth for semi-intensive roofs ranges from 120 to 250 mm, and they have a moderate weight range of around 120 to 200 kg/m^2. These roofs provide similar advantages as extensive GRs while also accommodating more diverse vegetation (Livingroof.org, 2016).

Figure 10: Semi-intensive green roof in Olympia, US (OlympiaGreenRoofs, 2023).

Intensive

Intensive GRs are designed for versatile garden and park purposes, allowing for a variety of plant types including perennials, shrubs, and even trees. The deeper substrate, ranging from 150 to 400 mm, supports the growth of larger and more complex vegetation. As a result, these roofs are heavier, with weights spanning from 180 to 500 kg/m^2. They offer a comprehensive range of benefits including water retention, thermal insulation, biodiversity support, and aesthetic appeal. However, they tend to be associated with higher installation costs due to the more intensive vegetation and engineering required (Livingroof.org, 2016).

Figure 11: Intensive green roof (Optigruen, 2023)

Sloped Roofs

Most of the roofs in general are sloped for automatic water drainage at 2° to 5°, sometimes also reaching up to 45° (depending on the structure of the roof) which is to be mostly avoided for GRs due to the increasing risk of slipping and displacement of bulk material. Extensive, Semi-Intensive, and Intensive are all sloped GRs.

Blue-green Roof

A blue-green roof (BGR) or rainfall retention roof is a non-sloped roof designed specifically for the retention of rainwater above the waterproofing element of the roof. This is as opposed to more conventional roofs which allow for rainwater to drain from the roof. BGRs are typically flat, without any falls, with control devices that regulate drainage outlets that enable water to be retained or drained (Dan Rigamonti, 2021). These roofs have a water retention layer generally made up of a geometrical grid-like structure for high strength; imparting lightweight to delay the water flow which can be used in the evapotranspiration process, by the plants without irrigation, and for reducing stormwater stress on channels.

Figure 12: Sectional view of intensive blue-green roof for greater detention (Optigruen AG, 2022).

2.4 Green Walls and its Types

Green walls (GWs), alternatively known as living walls, green facades, bio walls, or vertical vegetation, encompass vegetation that thrives directly on a building's facade or a distinct structural system. This system can either stand independently nearby or be affixed to the wall. Vegetation that is cultivated in planter boxes and guided by a freestanding or attached trellis system, installed with an automated irrigation component, is also categorized under the term 'green walls' (Loh, 2008).

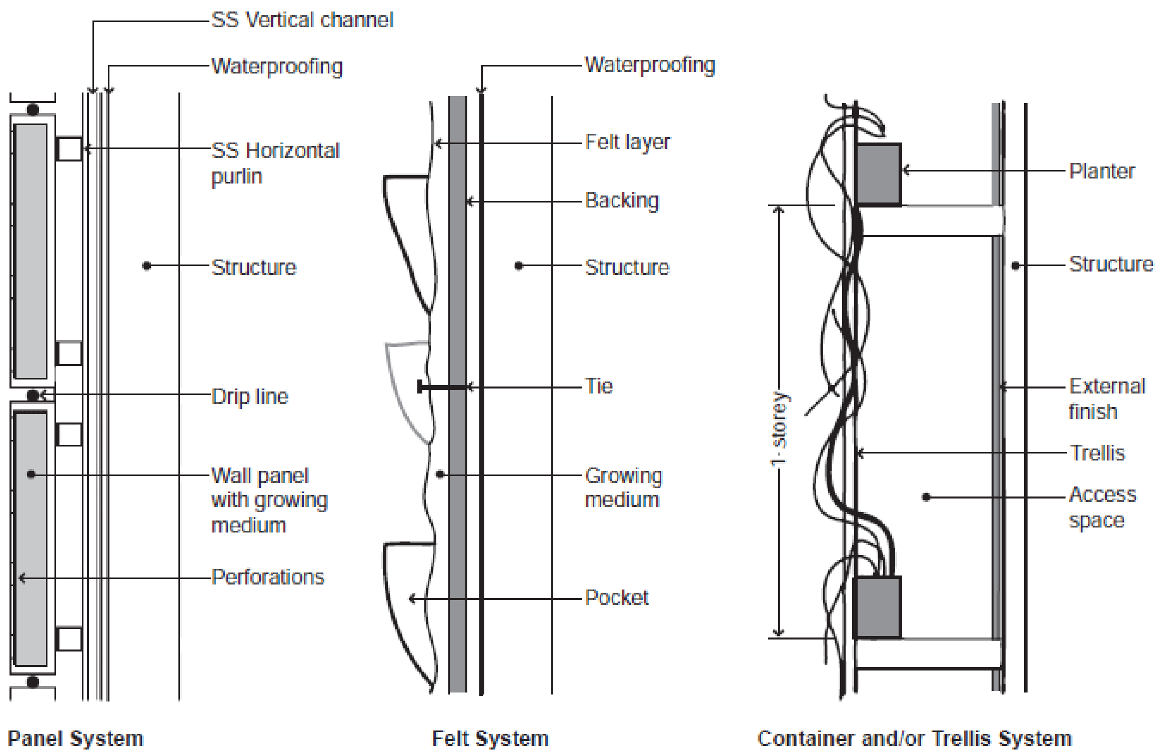

Figure 13: Section details of three generic green wall systems (Loh, 2008).

Panel System

A type that typically consists of pre-planted panels that are transported to the site and linked to the structural system along with a mechanical watering system.

Container / Trellis System

A type where plants grown in containers climb onto trellises. Irrigation drip lines are usually used in the plant containers to control watering and feeding.

Felt System

A setup in which the plants are placed within felt pockets filled with a growing medium and affixed to a waterproofed surface, which is subsequently linked to the supporting structure. The felt remains consistently hydrated with water containing essential plant nutrients.

Interior Living Walls

These walls are installed in the interior of the buildings and can be constructed using any of the three mentioned systems and may be intentionally linked to the building's mechanical setup. The living wall allows both recycled and fresh air to enter the building's interior, subsequently purifying and humidifying the air through the presence of plants and the growth medium. They are generally grown in either panel systems or container systems for ease of maintenance and less complex installation.

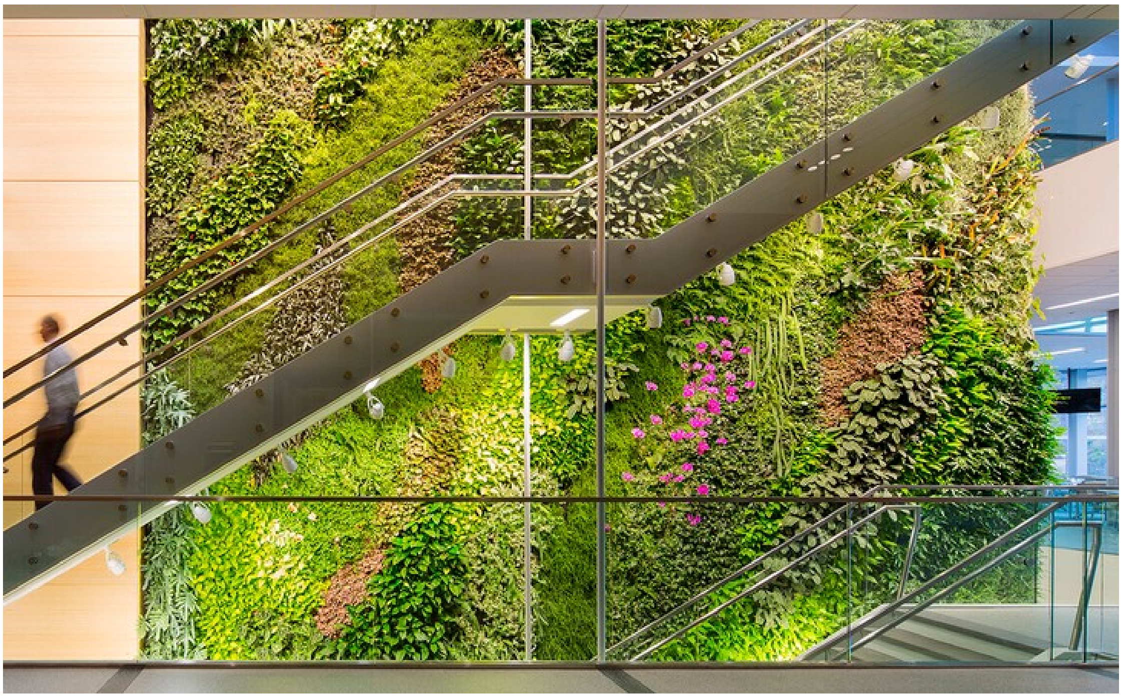

Figure 14: Installed interior living walls in an office building (Urbanstrong, 2023).

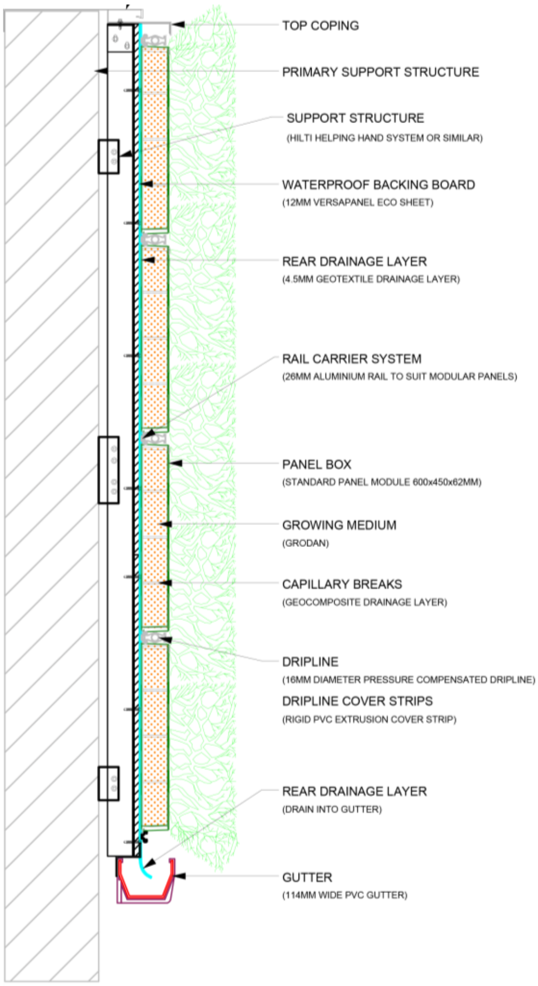

Figure 15: Interior Living Walls section (Biotecture Ltd, 2024)

Hydroponics

This system is a soilless system where the plants are grown in controlled environmental conditions such as temperature, pH balance, water, and nutrients. The plants are provided only and exactly what they require through nutrients dissolved in water which is carefully monitored and adjusted according to the plant type. These systems generally require high maintenance (Brock Robinson, 2019).

Figure 16: Hydroponics plants (Brock Robinson, 2019)

2.5 Factors affecting the performance of Green Walls and Green Roofs

Multiple factors are responsible for the performance of GWs and GRs broadly based on climatic conditions. The precise relevant factors are given below in the order of their dependency:

Evapotranspiration

This process considers the evaporation of the water contained in the substrate and the water used by the plants in their transpiration process. This means the water present on the roof turns into water vapor thus absorbing energy. As a result, this process cools the surface of the vegetative roof, decreasing the heat flux towards the interior of the building. Evapotranspiration is primarily generated by solar radiation, but it is also influenced by vegetation properties (e.g., stomatal resistance, albedo, and Leaf Area Index), other environmental conditions (e.g., air temperature, wind speed, and relative humidity), and available substrate moisture. The evapotranspiration cooling from GR and GW is directly proportional to the surface area available for its application (Satumane et al., 2018). The rate of evaporation is inversely proportional to relative air humidity, higher air humidity causes less evapotranspiration in green roofs (Water Science School, 2018).

Foliage Thickness and Leaf Area Index (LAI)

It is a quantitative trait that is associated with the ability of plants to occupy dry, high-irradiance environments (Coneva & Chitwood, 2018). Leaf Area Index is a common metric used to represent the total leaf area per unit of ground surface area. It provides an indirect measure of foliage density. Canopy cover is the percentage of the ground covered by the vertical projection of the outermost perimeter of the foliage. It estimates how much of the ground surface is shaded or sheltered by vegetation (Bréda, 2008). Foliage thickness has proved to be an important factor in the performance of GRs as well as GWs. This is because broader leaves reflect and absorb a certain amount of solar irradiance (Li et al., 2019). A variation from an LAI value of 1.0 to 5.0 generates a variation of 133.9 Wh/m^2, while the variation of the plant coverage from 50% to 100 % is about 60.32 Wh/m^2 (Cuevas & Ignacio, 2017).

Shading of Vegetation

Vegetation provides a layer that shades the substrate. For this reason, the radiation absorbed by the roof and its surface temperature is lower. This contributes to reducing the heat fluxes through the roof towards the interior of the building, and therefore its cooling loads. Weng (2014), as cited in (Cuevas & Ignacio, 2017), showed that 60% of the radiation that reaches the vegetative roof is absorbed by the vegetation and used for the evapotranspiration process, whereas 20% is reflected, thus transmitting only 20% to the substrate.

Thermal Insulation of the Substrate

The implementation of an extra material layer decreases the U-value of the roofing system. As a result, reductions of the heat fluxes through the roof can be achieved. This phenomenon depends directly on the type of substrate considered and its moisture content. One crucial element or thing to note is that the thermal conductivity of the substrate depends on the moisture content of the layer. According to Sailor and Hagos (2011), depending on the substrate's composition and increment of the volumetric water content (VWC) from 0 m^3/m^3 to 0.25 m^3/m^3 can increase the substrate's thermal conductivity between 0.15 W/mK and 0.55 W/mK. The effect of the substrate's thermal properties on the heating loads is directly related to the substrate's thermal conductivity. However, substrate influence on the cooling loads depends on its thermal diffusivity. This explains the fact that lightweight substrates and heavyweight substrates have very similar cooling loads but very different heating loads (Cuevas & Ignacio, 2017).

Substrate and Thermal Inertia

The substrate contributes to thermal mass that helps to stabilize indoor temperatures. For this reason, there is a reduction in the peak loads. The main substrate parameters that affect the cooling energy performance of a building are the heat capacity and the density. A variation from 1000 J/kg K to 3000 J/kg K for the heat capacity, and from 500 kg/m^3 to 1500 kg/m^3 generates a variation of 40.89 Wh/m^2 (Cuevas & Ignacio, 2017).

Stomatal Resistance

This parameter is an indicator of the metabolic relation between the plant and the environment. The value of the stomatal resistance depends directly on the amount and size of the plant's stomas and the metabolism of the plant. The stoma is a microscopic opening that controls the water vapor and carbon dioxide exchange rate. The guard cells surrounding the stoma are responsible for the stomatal resistance value (Heidarinejad and Esmaili, 2015) as cited in (Cuevas & Ignacio, 2017).

Among the models that consider this parameter, there are two different groups: the models that calculate it considering the VWC (Volumetric Water Content), and the ones that do not. This is a very important difference, as the stomatal resistance of a plant is directly associated with the amount of water available for the vegetation. If the substrate is dry, the plant does not have enough water for evapotranspiration, and it will close its stomata to conserve water. This increases the value of stomatal resistance. Therefore, there is an inverse proportionality between the VWC and the stomatal resistance (Cuevas & Ignacio, 2017).

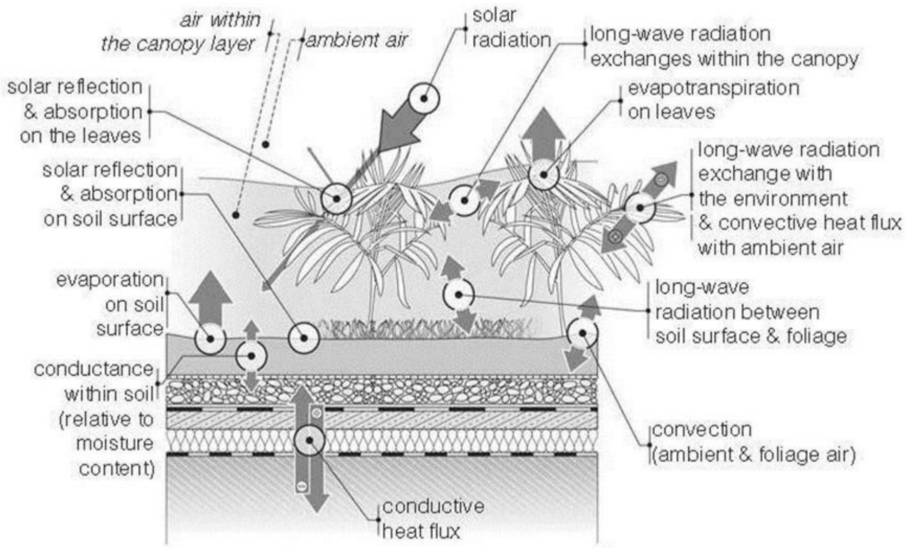

Figure 17: Heat flux in different types of roofs (Satumane et al., 2018)

2.6 Green Roofs as a Heat Mitigation Strategy

As already mentioned in the Research Framework, numerous scientific papers, journals, reports, and experiments were studied. The results of the relevant studies for GRs are as follows:

Performance evaluation of green roof in Haryana (Kumar & Kaushik, 2005)

Experimental observations on GRs in Panipat, Haryana, highlight the pivotal role of the Leaf Area Index (LAI) in enhancing the performance of extensive GRs in India's climate. The state has a subtropical, semi-arid to subhumid, continental climate with a monsoon pattern, the closest to New Delhi among all the included studies.

Figure 18: Schematic of the experimental site (Kumar & Kaushik, 2005)

Notably, the study underscores the critical influence of LAI in optimizing extensive GR functionality in Indian conditions. Utilizing GRs with solar thermal shading led to a remarkable reduction of up to 9.2°C in canopy air temperature. Simultaneously, the use of such roofs resulted in an average indoor air temperature reduction of 5.1°C. The study identified a cooling potential of 3.02 kWh as suitable for maintaining a temperature of 25.7°C.

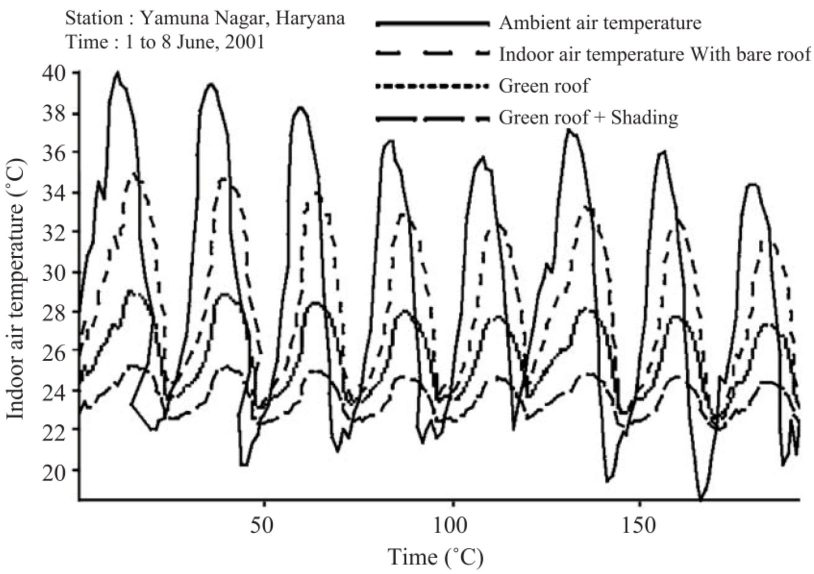

Figure 19: Resultant indoor air temperature variation graph (Kumar & Kaushik, 2005)

Kumar and Kaushik's (2005) experimentation in Panipat, Haryana, elucidates the crucial role of vegetation density, as represented by LAI, in enhancing extensive GR performance within India's climate. The pronounced temperature reductions across the canopy and indoor air underline the substantial cooling benefits these roofs offer. Furthermore, the identified cooling potential aligns with practical energy-saving considerations, advocating for the integration of extensive GRs as a sustainable response to climatic challenges.

Cooling potential of green roofs in hot dry climates (Jamei et al., 2021)

In 2021, Jamie et al. conducted a comprehensive study summarizing 89 research efforts spanning the years 2000 to 2020. The study encompassed three primary climate categories:

hot-humid, temperate, and dry. It is to be noted that Melbourne, Australia where the study took place has a temperate oceanic climate (Köppen climate classification Cfb).

The study's findings indicated that extensive GRs exhibit the greatest air temperature reduction potential in hot and dry climates, outperforming the other two climate types. In the summer season, these roofs in hot dry climates achieved a substantial 4.4°C reduction. Remarkably, for surface temperatures, hot-humid climate zones demonstrated the highest potential for temperature reduction.

Jamie et al.'s recent study provides valuable insights into the performance of extensive GRs across diverse climate types. Their findings emphasize the capacity of such roofs to significantly mitigate air temperatures, particularly in hot dry climates. The substantial reduction of 4.4°C underscores the potential impact on UHI effects and cooling strategies. Additionally, recognizing the heightened potential of hot-humid climates for surface temperature reduction highlights the adaptability of GRs in various environments. The study's overview of multiple studies spanning two decades further bolsters the credibility of their conclusions.

Cooling potential in Madurai, India (Madhumathi et al., 2016)

In a study conducted in Madurai, India, which is characterized by a tropical and dry season from January to March and a rainy season from September to November where the temperatures range from 18°C to 40°C and consistently high humidity, the performance of extensive GRs was examined.

The research findings highlighted the effectiveness of extensive GRs in this climate. Remarkably, an average temperature difference of 6.2°C was achieved between internal and external surface temperatures. Additionally, external air temperatures experienced an average reduction of 5.46°C.

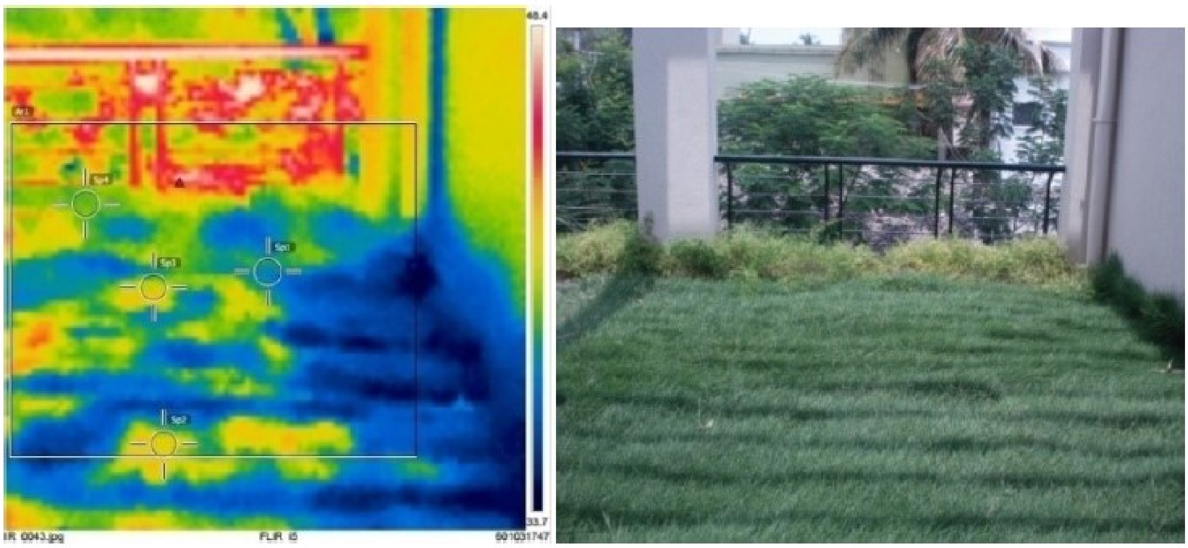

Figure 20: Experimental green roof setup with a thermal image (Madhumathi et al., 2016).

Madhumathi et al. 's (2016) study conducted in Madurai provides valuable insights into the benefits of these roofs in a climate known for their heat and humidity. The significant temperature differences observed between internal and external surfaces underscore the roofs' potential to enhance thermal comfort indoors.

Thermal performance of GR in Nagpur (Vinod Kumar & Mahalle, 2016)

The experimental investigation was carried out in Nagpur, India, by RTM University Nagpur. The study focused on warm days in this region, characterized by a tropical wet and dry climate. Nagpur, in general, has a tropical wet and dry climate (Aw in Köppen climate classification) with dry conditions prevailing for most of the year.

According to the study findings, during the hot summer days, an extensive GR demonstrated its capability to lower indoor air temperatures by up to 4.4°C compared to a traditional RCC roof. This reduction was observed when the maximum recorded outdoor air temperature reached 32°C.

Figure 21: Experimental green roof setup with symmetrical standard roof (Vinod Kumar & Mahalle, 2016).

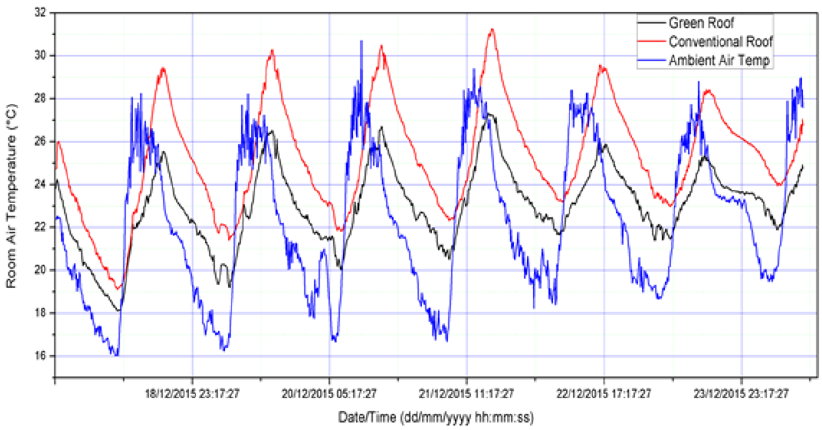

Figure 22: Resultant graph with room air temperature difference (Vinod Kumar & Mahalle, 2016).

This outcome underscores the effectiveness of employing extensive GRs in mitigating indoor heat during high-temperature periods. Interestingly, the study also delved into the role of substrate depth. It was determined that for optimal performance, the substrate depth should exceed 10 cm. Intriguingly, varying soil depths of 20, 30, and 40 cm yielded comparable reductions in room temperature, indicating that benefits remained consistent across these variations.

The research further revealed a distinctive aspect: a time lag of 2-3 hours persisted within the roofs, even after outdoor temperatures had subsided. Despite this time lag, the study emphasizes that the advantage of temperature reduction during peak hours outweighs the minor inconvenience introduced by the lag.

Energy Consumption of Green Roofs in Singapore (Wong et al., 2003)

Wong et al., 2023 conducted a field study in a Singaporean low-rise commercial building, revealing significant temperature reductions through GR implementation. This study observed a 3-4°C reduction in indoor temperature, varying based on plant types and the density of the Leaf Area Index. Evapotranspiration's latent flux played a vital role, particularly noticeable when the soil was nearly dry. The GR demonstrated a 60% thermal gain attenuation beneath the room compared to traditional roofing.

Wong et al.'s research highlighted the substantial impact of GRs on temperature control. Notably, reductions of 15°C– 45°C in daily peak surface temperatures and up to 5°C in peak air temperatures were reported. The study emphasized that energy demand reduction ranged from 8%– 80%, influenced by climate conditions and roof insulation. These findings underscore the potential for GRs to significantly contribute to energy-efficient building practices.

Evapotranspiration in Maritime climate - Hamburg (Dickhaut & Richter, 2023)

Hamburg has a Marine west coast, warm summer (Köppen climate classification: Cfb). The experimental study which lasted for about 6 years, depicted that blue-green roofs were able to evapotranspirate between 56% to 74% of the precipitated water collected on the roof. BGRs were capable of maintaining considerably higher soil moisture as compared to other GR types. This means that stormwater retention in GRs can increase the duration and chances of plant survival in hot-dry climatic regions without the need for artificial irrigation. This in turn also helps in the growth of diverse vegetation on the GR, and the cooling effect may prove to be consistent for longer dry periodic conditions.

Figure 23: Different green roofs set up in the study area (Dickhaut & Richter, 2023).

Plant survival on green roofs (Melbourne) (Guo et al., 2021)

The survival of plants on GRs can be enhanced through various strategies aimed at increasing water availability. These methods include irrigation, improving substrate water retention properties, using deeper substrates, or selecting plants with higher water availability due to their succulent nature (Farrell et al., 2012; Razzaghmanesh et al., 2014b, as cited in Guo et al., 2021).

According to (Farrell et al. (2012), Razzaghmanesh et al. (2014b), as cited in Guo et al., 2021) and other studies, plant survival on green roofs can benefit from practices that enhance water availability: "Plant survival on green roofs can be improved by increasing water availability through irrigation, improved substrate water retention properties, greater substrate depths, or by selecting plants that have greater water availability through succulence" (Farrell et al., 2012; Razzaghmanesh et al., 2014b, as cited in Guo et al., 2021).

This quotation underscores the significance of water availability and substrate depth in enhancing plant survival on GRs. The authors highlight several strategies, including irrigation and choosing plants with inherent water-retaining qualities. These efforts aim to address the challenges of water scarcity in rooftop environments, ultimately promoting the viability of plant life in these conditions.

Furthermore, studies by Dunnett et al. (2008), Kazemi and Mohorko (2017), and Eksi and Rowe (2019), as cited in (Guo et al., 2021) suggest that plants thriving in deeper substrates tend to exhibit improved survival rates and growth due to the increased water storage capacity and enhanced root space. However, it's worth noting that some research, such as that of Thuring et al. (2010) and Zhang et al. (2014), as cited in (Guo et al., 2021), indicates that plants can survive equally well in shallower substrates. This phenomenon may be attributed to the efficient access of water by shallow-rooted plants to retention layers below the substrate, as observed by Savi et al. (2015), as cited in (Guo et al., 2021). Additionally, plant traits linked to resource conservation, such as high wood density, high succulence, small specific leaf area, or small specific root length, often result in greater survival rates when water is scarce.

Herbs have been reported to survive better on GRs as they can maintain their water status and avoid drought stress through early stomatal closure (Farrell et al., 2013, as cited in Guo et al., 2021). Across all species, shrubs, and sub-shrubs survived better than herbs; greater succulence (leaf and plant water content) was associated with greater mortality in 15, 20, and 25 cm deep substrates (i.e., succulence was positively correlated with mortality scores), and greater leaf thermal tolerance (T50) was associated with higher mortality in 15 cm deep substrates.

GR performance with different substrates in the Mediterranean climate (Porcaro et al., 2019)

The climate in Córdoba, Spain is warm and temperate. There is more rainfall in the winter than in the summer in Córdoba and according to Köppen and Geiger, this climate is classified as Csa. The experimental findings provide valuable insights into the impact of GRs on heat reduction and cooling potential in warm and dry climates. The research observed that the three plots equipped with GRs exhibited substantial reductions in the Decrement Factor, which quantifies heat flow between wall surfaces. These plots also experienced notable increases in Cooling Potential, particularly suitable for warm and dry climates. In the study, three different substrates were employed: (a) a combination of 75% commercial growing medium and 25% recycled construction material, (b) a mix of 50% commercial growing medium and 50% recycled construction material, and finally, (c) a substrate consisting entirely of 100% commercial growing medium.

The research findings underscore that substrate composition significantly influences GR performance. The 100% commercial growing medium substrate stood out due to its excellent water retention, resulting in notable reductions in Decrement Factor and increased Cooling Potential. This highlights the pivotal role of water retention in achieving thermal benefits in warm, arid climates. The study emphasizes that greater substrate water retention leads to amplified heat reduction and improved cooling potential. Additionally, factors like fractional vegetation coverage, leaf area index, substrate composition, and water accumulation in drainage layers collectively contribute to delaying temperature peaks, enhancing the roof's thermal moderation.

Performance and usage of recycled materials in the green roofs (Rincón et al., 2014)

A study conducted by Gabriel Perez et al. (2011) as cited in (Rincón et al., 2014) at the University of Lleida explored the utilization of recycled rubber from tires as an alternative drainage layer for GRs, replacing traditional porous stone materials.

Perez's study concluded that extensive GRs offer energy-saving potential during summer in a Continental Mediterranean climate. The research demonstrated the viability of using rubber crumbs instead of Pozzolana as a drainage material. This substitution not only reduces the need for energy-intensive natural materials but also addresses the challenge of waste tire rubber disposal.

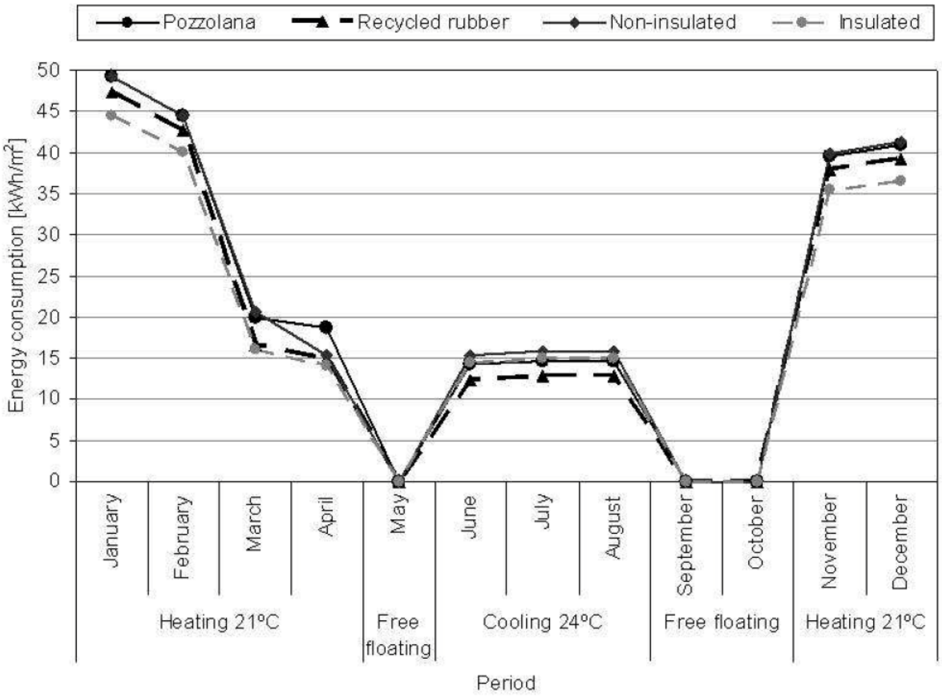

Figure 24: Graph depicting the lowest energy consumption of recycled rubber for cooling (Rincón et al., 2014).

Perez et al.'s investigation emphasizes the practicality of innovative materials in GR construction. By replacing traditional drainage layers with recycled rubber, the study not only showcased the feasibility of energy-efficient extensive GRs but also provided an environmentally friendly solution for repurposing waste rubber. Notably, the GR with recycled rubber achieved exceptional energy performance during peak solar radiation, resulting in substantial energy savings. The comparison against other roofing types further highlighted its advantages, with energy savings of 13% compared to pozzolana-based GRs, 14.8% against insulated conventional roofs, and an impressive 19.5% against non-insulated conventional roofs.

Energy simulation in semi-arid climates (Cuevas & Ignacio, 2017)

Vegetation is more effective than insulation in reducing cooling loads due to the evapotranspiration of the vegetation-substrate system and the canopy’s shading effect. Uninsulated GRs not only mitigate the absorption of solar heat by the roof but also facilitate the release of internal heat generated during periods of peak internal heating. Furthermore, the presence of thermal insulation can diminish the GR's capacity to lower cooling demands. However, since the climatic conditions of the region include a short period of very cold days, insulation is not used primarily in building construction which is also true for New Delhi, India.

2.7 Green Walls as a Heat Mitigation Strategy

Thermal performance of vegetated exterior facades (Susorova et al., 2013)

Illinois has a humid continental climate (Köppen climate classification Dfa). The experiment illustrated that the presence of a plant layer on a building facade can be highly effective in diminishing several key factors: exterior surface temperatures on the facades, daily temperature fluctuations indoors, temperature variations across the exterior wall, and consequently, the heat transfer through the exterior wall. This effect is especially prominent during days with intense solar radiation. Sensitivity analysis further highlighted the significance of specific weather parameters, including solar radiation, wind speed, relative humidity, and outdoor air temperature, in descending order of importance.

Additionally, the analysis underscored that plant layers characterized by dense foliage (exhibiting high leaf area indices) and leaves oriented parallel to the wall (possessing high attenuation coefficients) are likely to yield the most favorable outcomes in terms of reducing facade surface temperatures and heat flux through the facades. On particularly hot and sunny days, the introduction of a plant layer on a brick facade was estimated to lower the exterior surface temperature by approximately 0.7°C to 13.1°C, leading to a decrease in heat transfer through the exterior wall by 2-33 W/m^2. Furthermore, it provided an effective R-value ranging from 0.0 to 0.71 m^{2}K/W, with the primary determinants being wall orientation, leaf area index, and radiation attenuation coefficient.

Figure 25: Depiction of experimental setup on the facade in Illinois Institute of Technology (Susorova et al., 2013)

Measured facade properties		8/29	8/30	8/31	9/1
Difference in exterior surface temperatures (°C) (bare vs. vegetated wall)	Max	7.9	6.6	5.7	1.3
	Ave	1.6	1.2	1.1	0.4
Difference in interior surface temperatures (°C) (bare vs. vegetated wall)	Max	2.0	1.1	1.7	1.3
	Ave	1.5	0.6	0.7	0.8
Difference in outside air temperatures (°C) (bare vs. vegetated wall)	Max	2.9	4.0	3.3	0.5
	Ave	0.9	−0.5	−0.5	−0.3
Temperature difference between the exterior and interior wall surfaces (bare wall) (°C)	Max	7.1	17.1	16.1	3.6
	Ave	2.04	4.65	4.77	1.48
Temperature difference between the exterior and interior wall surfaces (vegetated wall) (°C)	Max	5.0	13.3	11.4	2.9
	Ave	1.97	3.98	4.41	1.84
Difference in wall temperature gradients (°C) (bare vs. vegetated wall)	Max	6.1	6.2	5.5	0.9
	Ave	0.07	0.67	0.36	−0.35

Figure 26: Measured thermal properties of the bare and vegetated facades (Susorova et al., 2013)

Thermal Impacts of Vertical Greenery Systems - Malaysia (Safikhani et al., 2014)

The experimentation study took place in Malaysia where the highest temperature is 34°C with 85% relative humidity, where the climate is classified as (Köppen climate classification Af), a hot, humid tropical climate with all months above 18°C. The following are the results of the experiments:

1. During the hottest time of the day, the living wall and green facades were able to reduce the cavity temperatures by 8°C and 6.5°C respectively. Whereas, the indoor air temperature experienced a temperature reduction of 4°C and 3°C respectively.
2. This proves that there is a positive impact of vertical greenery on indoor temperatures in hot, humid climates.
3. The temperature behind the GF was about 0.5°C higher because the plants and foliage of the GFs were directly connected to the wall surface, acting as a barrier and not allowing warm inside air to ventilate via the wall surface.
4. A negative effect on humidity control was observed for both the GFs as well as living walls. The cavity between the leaves and wall had higher humidity in the case of the GF because of the interference of leaves and foliage with evapotranspiration.
5. In future experimentations, considerations about denser foliage for GFs can potentially increase performance.
6. Natural ventilation can increase thermal comfort in outdoor spaces.

TEMPERATURE REDUCTION PROVIDED BY THE LIVING WALL AND GREEN FACADE

	Cavity Air Temp.	Indoor Air Temp.	Indoor Air Temp. when Ventilation is Being	Cavity Surface Temp.	Indoor Surface Temp.
Living wall	8.0 °C	4.0 °C	3.5 °C	6.3 °C	4.0 °C
Green Facade	6.5 °C	3.0 °C	2.5 °C	5.5 °C	3.5 °C

Figure 27 depicts the temperature reduction between the living wall, green facade, and standard brick wall (Safikhani et al., 2014).

It is to note that the location and temperature of the place where the experiment took place, had the highest temperature of 34°C. It is likely that in the current study area, New Delhi where temperatures are reaching 49°C, the temperature reduction might be higher than 4 degrees.

Passive Cooling Strategies for High Thermal Performance Buildings in Hot Climate (Haggag et al., 2014)

According to Köppen and Geiger, Abu Dhabi's climate is classified as BWh and is considered to have a desert climate with very little rainfall. The case study is in UAE where the maximum average temperature is 43.8°C. The use of GWs was successfully adopted in the Emirate of Abu Dhabi, UAE to increase energy efficiency in buildings and reduce environmental impact. The decreased temperature on the GFs is achieved by:

- Reduced heat gain results from the GW as the plant leaves, soil mass, and the structure supporting the plants block incident radiations.
- The evaporative cooling caused by the irrigation water to the plants.
- Heat resistance due to the low thermal conductivity of the plants acting as heat insulators to the ambient heat gain by the wall.

This technology can lower indoor air temperatures during peak times by a minimum of 5°C in July, leading to a potential reduction of up to 20% in peak air conditioning energy demand. In a final assessment, the heat gain from the GW test room was analyzed to determine the cooling load and compare it with that of a non-vegetated (bare) wall. The findings indicate that the cooling load decreased from 1.35 MWh to 1.07 MWh, resulting in a 20.5% energy savings for cooling attributed to the GW.

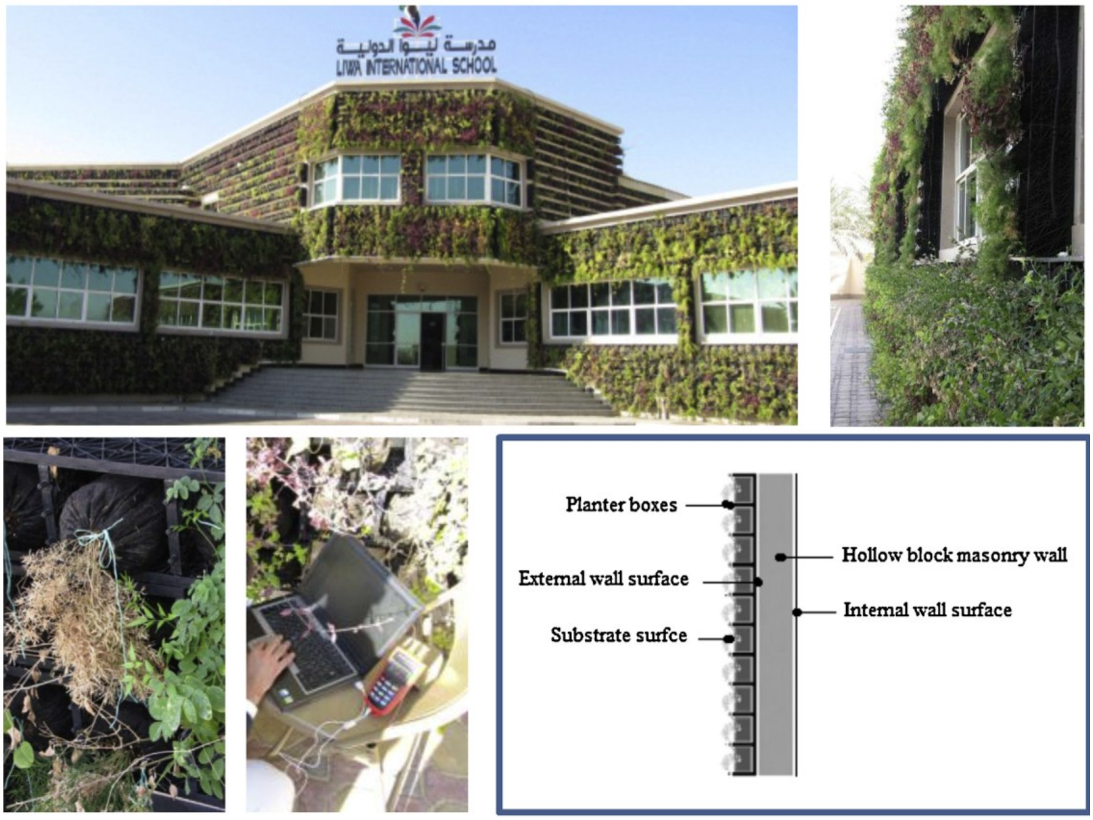

Figure 28: Installation setup of the green walls on the building facade in Liwa International School (Haggag et al., 2014).

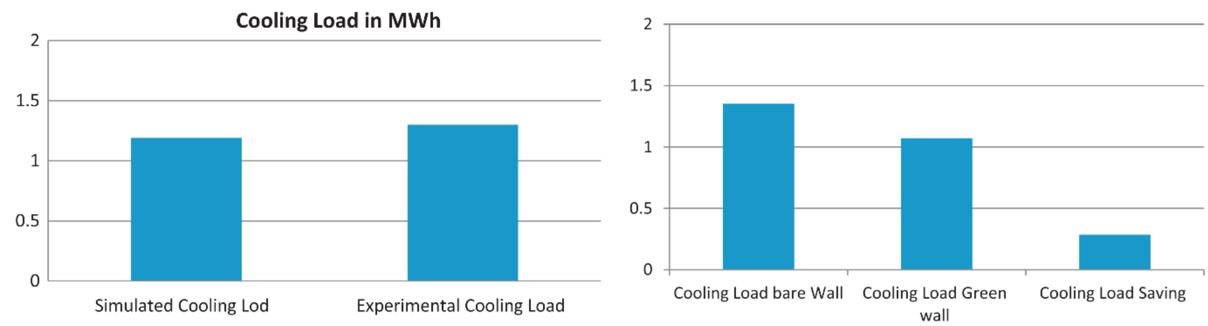

Figure 29: Graphical representation of the savings in cooling loads in MWh (Haggag et al., 2014).

The research highlights the advantageous aspects of passive cooling approaches, offering advantages not only for environmental preservation but also for cutting down on cooling requirements and air conditioning expenses. The study's experimental outcomes indicate that methods involving vegetation and shading from plants can lower indoor air temperatures during peak times by a minimum of 5°C in hot summer conditions. Furthermore, these methods can result in a reduction of up to 20% in peak air conditioning energy demand when employing vegetated living walls and 18.5% when using plant-shaded walls (Haggag, 2021).

Performance of Green Facades and Green Roofs (Satumane et al., 2018)

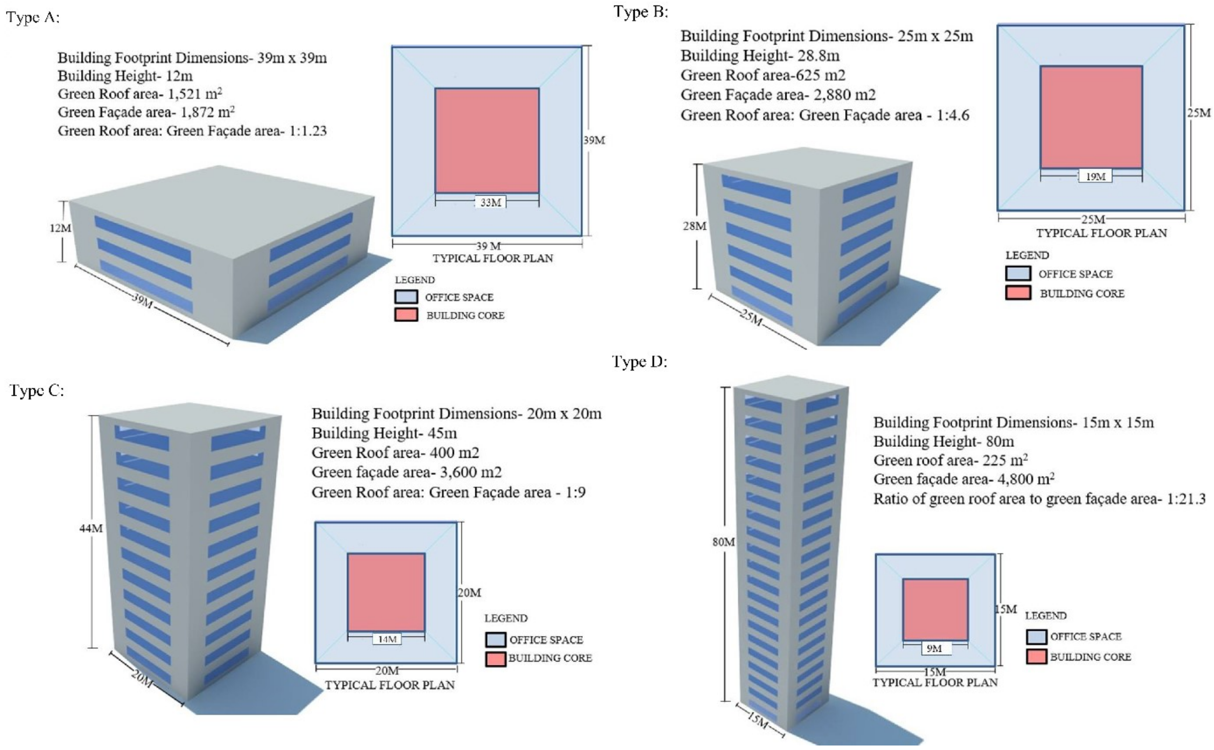

Figure 30: Depiction of different types of building models used for the simulation of the thermal performance of green walls and facades (Satumane et al., 2018).

Figure 28 shows the different building models for the simulation of the energy performance of GRs and GWs simultaneously. The results of the experiment clearly state that the higher the area of the building covered by a GR or GW on the roof or facade respectively, the higher the reduction in heat gain. This means that with a higher roof area, the reduction in heat gain to the building from the roof will be higher as compared to the facade and vice versa. Both greening systems provide almost the same cooling effect per unit area. Additionally, GFs are more functional for providing a cooling effect where direct sunlight is received.

Air Pollution Tolerance Index (APTI) of climber plants in India (Pandey et al., 2015)

An experiment was conducted in Varanasi, North India which has similar climatic conditions as New Delhi to study the Air Pollution Tolerance Index (APTI) in outdoor plant species which can be used in the vertical greening of the buildings. The result from the study depicted that the climber plants mitigate the deterioration of the walls by reducing contact between particulates and wall surfaces. Moreover, they reduce human exposure to vehicular pollutants. Research on common or English Ivy plants (Hedera helix L), revealed their effectiveness in trapping fine (<2.5 μm) and ultra-fine (<1 μm) particles, acting as a particulate matter sink.

The APTI of plants is determined by four key parameters: ascorbic acid content, leaf extract pH, total chlorophyll content, and Relative Water Content (RWC), which collectively assess a plant's tolerance to air pollutants. However, a high correlation for APTI exists only between the total chlorophyll content and the ascorbic acid content of the plant. Ascorbic acid, an antioxidant present in plant growth regions, influences resistance to adverse environmental conditions, including air pollution. Its activity is pH-dependent, with higher leaf-extract pH values indicating greater air pollution tolerance. Plants that maintain chlorophyll content in polluted conditions are considered tolerant. Vertical Greenery Systems (VGS) contribute to improved air quality by absorbing particulate matter and absorbing gaseous pollutants like SO_2 and NO_2. Sulfur and Nitrogen di-oxides are converted into sulfates and nitrates in plant tissues, while particulate matter (PM_{10}) adheres primarily to outer plant surfaces, such as leaves. Plants with APTI values lower than 13 are not recommended for VGS, as they are sensitive to air pollution. Likewise, plants with APTI values between 13 and 16 are not suitable for VGS in highly polluted areas but may thrive in moderately polluted regions. Conversely, tolerant plants with APTI values higher than 17 are suggested to be used in VGS.

Simulation of energy performance of a building with GR and GW in Chennai, India (Pragati et al., 2023)

Chennai has a tropical climate where the summers are much rainier than the winters and is classified as Köppen-Geiger climate Aw.

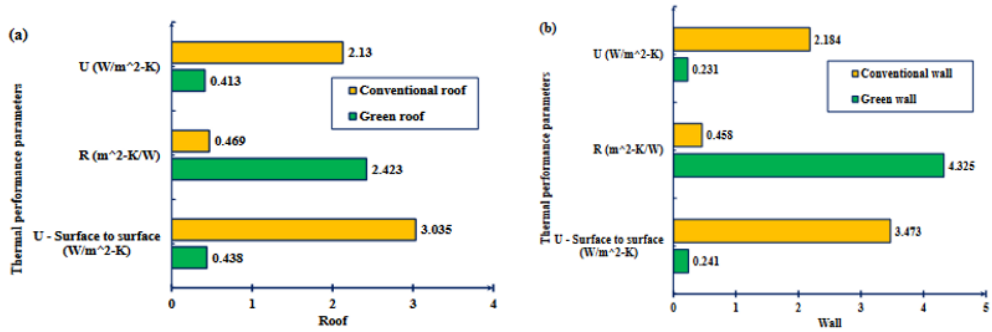

Figure 31: Comparison of thermal performance parameters of conventional and green envelopes from the current simulation study a) roofs and b) walls. (Pragati et al., 2023)

The comparison of energy consumption is carried out between conventional and green buildings. The cooling load of buildings covered with GWs and GRs was reduced by about 13% compared to conventional buildings. The site energy requirement of green buildings was reduced by about 10% compared to conventional buildings. The green envelopes act as thermal insulation against solar radiation and minimize heat transmission into the buildings. As a result, green buildings decrease the amount of solar heat gains and reduce the energy needed for air conditioning. The U-values of GRs and GWs decreased from 2.13 to 0.413 W/m²K and from 2.18 to 0.23 W/m²K respectively.

Influence of foliage thickness on thermal performance of green façades (Li et al., 2019)

The study was performed in Suzhou, China which has a humid subtropical climate with hot, humid summers and cool, cloudy, damp winters with occasional snowfall (Köppen climate classification Cfa). The experiment was performed with Boston Ivy green facades and the following are the findings from this study:

1. The Green Facade Systems have a notable cooling effect. According to field measurements, the surface temperature of the adjacent wall is reduced by a maximum of 6.3°C during the daytime and a minimum of 0.1°C during the nighttime compared to the bare wall situation.

2. Among the measurements taken with foliage thicknesses of 7.2 cm and 30.5 cm, the GF with a foliage thickness of 19.8 cm displays the most effective thermal performance. This can be attributed to the enhanced convective heat transfer occurring between the building envelope surface and the leaves of the plants in this configuration.

3. Ambient temperature above leaves was also influenced by the GFS. For GFS with foliage thicknesses of 7.2 cm and 19.8 cm, the air temperature above the leaves at a distance of 0.05 m was noticeably lower than the temperature of the bare wall. However, for GFS with a foliage thickness of 30.5 cm, the air temperature above the leaves at a distance of 0.05 m was noticeably higher. This discrepancy could be a result of the denser vegetation near the temperature sensor, potentially obstructing air circulation and causing an increase in air temperature. Conversely, the air temperature readings taken at a distance of 0.15 meters from the leaf layer were relatively consistent across the three Green Facade Systems (GFS), suggesting that they had a limited impact on microclimate regulation at that distance.

4. Relative humidity (RH) under the leaf layer increased significantly compared to the point on the bare wall, and the fluctuation was relatively smaller. There was an opposite RH gradient beneath the leaf layer compared to the temperature decline observed in GFS with varying foliage thicknesses. The RH of the air immediately above the leaves can be influenced by the GFS within a short distance, typically no more than 15 cm.

Figure 32: Experimental setup and measuring points on the facade (P1–small leaves covered area (average foliage thickness of 7.2 cm), P2–bare wall, P3–medium-sized leaves covered area (average foliage thickness of 19.8 cm), and P4–large leaves covered area (average foliage thickness of 30.5 cm)) (Li et al., 2019).

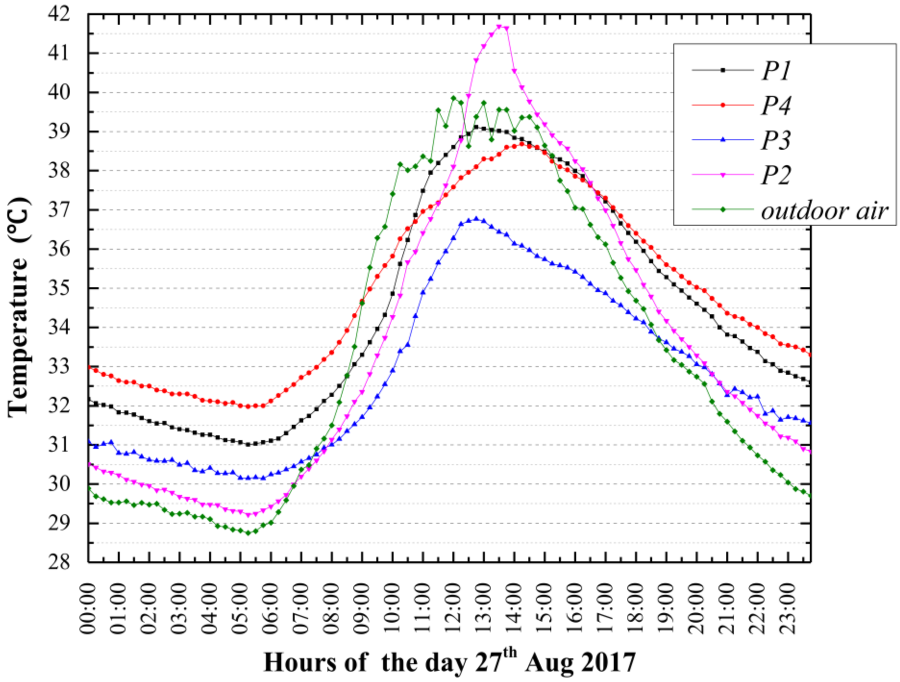

Figure 33: External wall surface temperature of P1, P2, P3, P4, and outdoor air (Li et al., 2019).

2.8 Substrates

The FLL Guidelines for GRs state that the crucial properties of the substrate include the drainage function, design load, organic matter content, water storage capacity, nutrient content, and adsorption capacity (FLL, 2018). Substrates can be used commonly for GRs and GWs as per the region and application since the requirements for both greening systems overlap.

Vijayaraghavan in his study stated that it is recommended to design the substrate for GRs using local waste materials, which can contribute to cost-effective installations. In regions where commercial GR products are unavailable, individuals often opt for locally accessible substrate mediums for establishing GRs, including garden soil and composts. Nevertheless, utilizing garden soil in GRs presents clear drawbacks:

- Inadequate water retention and aeration
- Excessive weight, raising the risk of roof collapse
- Facilitating weed growth
- Nutrient leaching and easy compaction

The complete reliance on 100% composts on rooftops should also be avoided due to potential consequences like the contraction of the vegetation support layer, unnecessary weed proliferation, heightened rooftop load during rainfall, and jeopardizing the overall roof's sustained success. Consequently, proper engineering of the growth medium is essential to attain positive outcomes (Vijayaraghavan, 2016).

The authors discovered that an increase in organic matter yielded enhanced plant growth and substrate moisture levels. However, the presence of organic constituents within the substrate frequently emerged as a probable origin of contaminants in GR runoff. This is mainly attributed to instability, as organic matter undergoes decomposition over time, leading to substrate contraction. According to Emilsson and Rolf, two distinct GR substrates utilizing 3% and 10% peat materials respectively, were largely decomposed within the first year. Consequently, it is advisable to minimize the proportion of organic matter within GR substrates. The German Guidelines for GRs by FLL recommend organic matter volumes of only 4–8% for extensive GRs and 6–12% for intensive GRs (Vijayaraghavan, 2016).

The growth medium's dry and wet bulk densities are critical factors. Among the various components, the substrate significantly impacts the load on the roof structure. Due to load limitations, especially in older buildings with roofs not designed for GRs, it is vital to minimize substrate weight. Employing low-density inorganic recycled materials is a primary strategy to achieve this. For instance, the bulk density of perlite is notably 9.4 times less than that of conventional garden soil (Vijayaraghavan & Raja, 2014). Some research guidelines advocate using over 80% inorganic constituents in GR substrate (FLL, 2018) as a means to reduce overall weight. It's noteworthy that lower substrate density allows for thicker substrate layers and a diverse range of vegetation (Xiao et al., 2014). Wet bulk density is also significant, as certain substrate components rapidly become saturated during rainfall, contributing to increased weight. Organic elements like coco-peat, for instance, can enhance their original weight by up to 5.2 times under maximum moisture conditions (Vijayaraghavan & Raja, 2014). Additionally, (Cao et al., 2014) reported a 4.1 times increase in bulk density for biochar upon saturation.

Material (main components)	expanded shale, expanded clay, lava, pumice, crushed brick, Porlith and green waste compost. With a variable composition depending on the region.
Weight when dry (compacted)	min. 670 kg/m³ (light version) min. 920 kg/m³ (heavy version)
Weight when saturated (compacted)	900-1,260 kg/m³ (light version) 1,180-1,490 kg/m³ (heavy version)
Max. water capacity	>= 20 Vol%
pH value	6.0 - 8.5
Salt content	<= 3.5 g/l
Water permeability	>= 60 mm/min
Compaction factor	1.15
Organic substances	< 40 g/l
Total pore volume	> 60 - 70 Vol%
Delivery form	- loose bulk on an open truck - blown into silo truck - in big bags on an open truck - In sacks on euro pallets by forwarding agent

Figure 34: Technical specifications of commercially available Extensive substrate by Optigruen (Optigruen, 2023).

Material (main components)	expanded shale, expanded clay, lava, pumice, crushed brick, Porlith and green waste compost. With a variable composition depending on the region.
Weight when dry (compacted)	min. 830 kg/m³ (light version) min. 1,000 kg/m³ (heavy version)
Weight when saturated (compacted)	1,300-1,480 kg/m³ (light version) 1,490-1,560 kg/m³ (heavy version)
Max. water capacity	>= 45 Vol%
pH value	6.0 - 8.5
Salt content	<= 2.5 g/l
Water permeability	>= 0.3 mm/min
Compaction factor	1.3
Organic substances	< 90 g/l
Total pore volume	> 60 - 75 Vol%
Delivery form	- loose bulk on an open truck - blown into silo truck - in big bags on an open truck - In sacks on euro pallets by forwarding agent

Figure 35: Technical specifications of commercially available Intensive substrate by Optigruen (Optigruen, 2023).

Material (main components)	lava, pumice, peat
Weight when dry (compacted)	980 kg/m³
Weight when saturated (compacted)	1,340 kg/m³
Max. water capacity	36 Vol%
pH value	7.02
Salt content	0.1 g/l
Water permeability	101 mm/min
Compaction factor	1.15
Organic substances	1.5 mass%
Total pore volume	63 Vol%
Construction material class	A1 (not flammable)
Delivery form	- loose bulk on an open truck - blown into silo truck - in big bags on an open truck

Figure 36: Technical specifications of commercially available Semi-Intensive substrate by Optigruen (Optigruen, 2023).

The figures above depict the technical properties required by different substrate types according to the requirements set by FLL Guidelines. The values from the figures can be used as reference values to develop a locally sourced substrate that is more sustainable, less energy-intensive, cost-efficient, and potentially abundant in nature to meet the high demands.

The authors in this experiment conducted an extensive study aimed at creating a substrate blend by incorporating diverse inorganic and organic elements. A mixture composed of 30% perlite, 20% vermiculite, 20% crushed brick, 10% sand, and 20% coco-peat on a volume basis demonstrated favorable traits as a GR substrate. These characteristics incorporated low bulk density (431 kg/m^3), high water-holding capacity (39.4%), air-filled porosity (19.5%), hydraulic conductivity (4570 mm/h), and maximal support for plant growth (380% total biomass increment) (Vijayaraghavan, 2016).

There are a variety of commercial substrates available in the global market and are generally categorized on the type of GR/GW system and weight of the substrate. However, in India, they are not readily available exclusively for GR and GW. Fortunately, there is a high availability of coconut by-products as a result of high coconut growth in some parts of the country. This offers a variety of potential substrates such as cocopeat, coir compost, and coco pith which are readily available in the country (Anandh International, 2023). Interestingly, the cocopeat substrate can be used for GRs and GWs. This substrate is a blend of cocopeat, perlite, and soil mix which has a high water-holding capacity, air-filled porosity, and lightweight, which favors better root growth, and low vulnerability to pests and diseases (Anandh International, 2023).

Below are examples of the products that were found to be in use regularly or have high potential to be used as substrate elements.

Coco coir, derived from coconut production waste, offers several advantages as a growing medium. It possesses an impressive water-holding capacity, surpassing peat moss, although it doesn't maintain this moisture as long. However, it's relatively easy to rehydrate once dried out. Coir's pH level, ranging from 5.8 to 6.8, aligns closely with the ideal range for many plants. Furthermore, it decomposes gradually over two to three years, enhancing soil aeration in the process. Coir exhibits a notable cation exchange capacity, allowing it to store and release nutrients gradually. While it serves as a sustainable substitute for peat moss, it lacks significant inherent nutrients and requires supplemental fertilization. It's a versatile medium, suitable for various applications, including potting soil and mulch. Nevertheless, its water distribution can be uneven, necessitating careful monitoring of moisture levels when watering plants (Drew Swainston, 2023).

Figure 37: Coco coir (Espiritu, 2016)

Perlite which aids aeration, provides drainage and insulation, and has good water retention properties is also readily available. It is generally used in synergy with peat-based composts and local soil (Sadhu Garden, 2016).

Figure 38: Perlite (Etsy, 2023)

Clay balls provide plants with plenty of oxygen for fast-growing roots, and they hold enough moisture within their micro-pores to allow for healthy water and nutrient retention from the roots to the top nodes (Sadhu Garden, 2016).

Figure 39: Clay balls or aggregates (Gaspard, 2023)

Vermiculite as a substrate mix enhances both water and nutrient retention while improving soil aeration, leading to the development of healthier and more vigorous plants. It is very similar to perlite however, it surpasses perlite in water retention capacity, making it the preferred choice for plants with higher water requirements, despite being somewhat less effective in soil aeration compared to perlite (Amy Grant, 2022).

Figure 40: Vermiculite (Amy Grant, 2022)

Even so, more thorough research is needed in this field and needs to be classified based on application, specific climatic conditions in India, local material availability, and soil type for it to be used for GRs and GWs.

2.9 Maintenance of Green Walls and Green Roofs

Selecting plants to be used in GRs or GWs depends on the climate, soil depth, and irrigation requirements. Some plants can tolerate heat and survive with little water quantities like succulents and sedums, whereas some plants need extensive irrigation to tolerate the heat like wetland plants and prairie plants. The selection of native plant varieties reduces the requirements of maintenance and irrigation that are usually needed with typical landscaping schemes. Native plants are usually irrigated during the establishment period only. The soil depth should be increased to accommodate native plant growth and vigorous root barriers may be needed to protect the roofing membrane from aggressive native roots (Satumane et al., 2018).

The usage of one species of plant can produce a uniform color, texture, and height. However, it is risky as Pests, and climate can attack that mono-crop GR and wipe it out without warning, so it is recommended to use plant diversity consisting of at least five species of plants (Luckett, 2009 as cited in (Satumane et al., 2018)). It is more sustainable to use plants with different leaf textures that have different water metabolism during different conditions. For instance, Leafy plants can tolerate heat and drought by storing large quantities of water in summer, dormancy in winter, and growth in spring. Plants that have needle-like leaves like Reflexum sedum and Album sedum remain colorful during the winter season (Satumane et al., 2018).

Evapotranspiration and rainfall retention exhibited comparable results in both half-planted and fully-planted modules, with approximately 82% of the applied rainfall being retained. Although both vegetation treatments led to substrate drying before rainfall, the fully-planted modules experienced a more rapid drying process and showed notably lower leaf water status compared to the half-planted modules. This suggests that planting at lower density could potentially alleviate plant drought stress without compromising rainfall retention. Additionally, the introduction of runoff zones had a marginal effect on reducing evapotranspiration and rainfall retention, likely because the structures of the runoff zones provided shading that reduced substrate evaporation (Soni et al., 2023).

Socio-Ecological Dimensions of Spontaneous Plants on Green Roofs (Schrieke et al., 2021)

Spontaneous GR communities exhibit significant biodiversity potential. If unmanaged, species richness surpasses initial plantings (refer to the figure below). "Spontaneous vegetation can also provide habitat for invertebrates and floral resources for pollinators." This underscores the ecological benefits associated with allowing natural growth on GRs.

When Sedum GR vegetation is replaced by these communities, it promotes greater butterfly diversity thanks to the consistent year-round flowering and the presence of easily accessible short-corolla flowers. This highlights the potential of spontaneous growth to enhance specific biodiversity elements. Integrating spontaneous vegetation can alleviate the substantial costs linked to installation and ongoing plant maintenance. Spontaneous species are established in shallow-substrate GRs. This outlines the financial advantages of incorporating spontaneous growth. However, spontaneous GRs necessitate maintenance. Costs arise from annual inspections of roofing membranes, drainage, and the removal of woody plants to prevent waterproofing damage. This emphasizes the practical considerations and expenses associated with such GR systems.

Relying solely on spontaneous vegetation for plant cover can come with disadvantages, particularly on tall buildings where height restrictions can limit access to the roof. This highlights the potential limitations in specific architectural contexts. Erosion and reduced energy and stormwater performance could result from low substrate cover and diversity due to insufficient propagule reach.

This indicates that lightweight GRs featuring shallow substrates that encourage natural colonization could provide socio-ecological advantages at a lower expense compared to traditional extensive GRs. Furthermore, there's potential for substantial reductions in maintenance and input costs, which could help mitigate issues related to "green gentrification" and the displacement of vulnerable communities by large-scale green infrastructure projects.

Spontaneous green roof vegetation traits	Social function	Ecological function	Trade-off
Prolonged flowering continuity[a]	Cue to care[e], ecological beauty[f], high preference[g]	Support butterfly biodiversity[a], floral resource for pollinators[h]	No clear trade-off
High biodiversity[b]	Biodiverse vegetation preferred[d], acceptance increases when residents informed of ecological function[i]	Habitat for rare insects and spiders[j], increased GR functionality[k–m]	Perceived messiness of naturalistic plantings[i]
Fast growth/ annual lifecycle[c]	Accumulation of organic matter when plants senesce perceived as 'messy'[i]	High transpiration[c] may increase stormwater mitigation	Accumulation of organic matter when annual plants senesce provides arthropod habitat[n]
Gaps in vegetation[d]	Significant negative impact on green roof aesthetic[d]	Gaps provide safe sites for plant colonisation[o]	Loss of transpiration and canopy cooling when vegetation senesces[p]
Low maintenance	Reduction to green roof costs, a significant deterrent to adoption[d]	No fertiliser, herbicide, or pesticide application	No clear trade-off

Colours represent perceived beneficial (green) and unfavourable (red) outcomes.

Figure 41: The social and ecological functions given by spontaneous plant growth along with its trade-offs (Schrieke et al., 2021).

2.10 Vegetation Selection

For Green Roofs

Plants:

Johnston & Newton (2004), as cited in (Satumane et al., 2018), outlined key parameters for selecting suitable plants for extensive GRs. They emphasized the importance of plants capable of establishing dense root systems and providing resilient ground cover. Given the elevated location of GRs, the growing medium should possess greater porosity and be lighter than that used in ground-level gardens. Plant selection should also consider geographic and environmental factors, including temperature fluctuations, shade availability, wind exposure, and solar radiation exposure.

In general, the most successful and suitable plant species for GRs are characterized by shallow root systems, low growth profiles, and perennial attributes, enabling them to thrive in diverse climatic conditions (Edmund and Lucie, 2006, as cited in (Satumane et al., 2018)). Additionally, these plants should require minimal maintenance and nutrient input, as installing a water reservoir at the bottom of the growing medium is often impractical, necessitating the ability to endure periods of heat and aridity.

Plants Types:

• Annuals- To make GRs cost-effective, annuals should not be the dominant plant because of their longevity. Annuals need at least 75 mm of regular rainfall and may need supplement irrigation.

• Herbaceous perennials- They are desirable plants for their aesthetic appeal and are available in a variety of textures and colors. They require moisture and deep substrate and their tolerance to heat, and dry conditions is limited.

• Hardy succulents are considered extensive roof workhorses with a growing medium of 100 mm or less. They have an excellent ability to tolerate wind and drought conditions, and their metabolism process can conserve water. These plants can open the stomata at night time to store carbon dioxide and close it at daytime which reduces transpiration losses.

• Grasses- The use of grass on GRs is still new. It adds texture and offers a habitat for insects and birds. They typically require a deeper growing medium than succulents.

• Herbs- Herbs require a growing medium of more than 60 mm and an irrigation system. They have good drought tolerance. They can be planted on the roofs of hospitals, restaurants, private residences, or institutional buildings and can be harvested for educational, therapeutic, aromatic, and culinary use.

Plants Selection:

Evergreen plants and seasonal flowering: When choosing plants, it's crucial to factor in the desired duration of green coverage. While hardy annuals can become self-sustaining after the first year, they tend to spread unpredictably on the roof. To achieve year-round greenery, it is advisable to use a mix of annuals, herbaceous perennials, and resilient succulents (Dennett& Kingsbury, 2008 as cited in (Satumane et al., 2018).

Accent plants versus Groundcover: GRs should primarily utilize ground cover with occasional accent plants. Ground cover plants are typically preferred for their reliability, rapid growth, and cost-effectiveness. Accent plants, while visually appealing, may not thrive for more than five years on the GR. In contrast to ground cover, accent plants provide seasonal interest, do not spread quickly, and require a larger number of plants to cover a given area. (Satumane et al., 2018).

Native plants: Native plants possess numerous qualities that make them highly suitable for green roofs. They readily adapt to local climatic conditions, are resilient against native diseases, are less susceptible to animal and insect harm, and contribute to the establishment of stable biodiversity (Satumane et al., 2018).

The importance of leaf succulence in plant selection (Rayner et al., 2016)

The University of Melbourne, which has seasonally hot and dry conditions, conducted experiments to see the importance of leaf succulence in plant selection and the conclusions of the study are as follows:

1. Survival Differences Among Species on GRs:
    - Succulents demonstrated the highest survival rates in the experiment.
    - Not all species survived, and substantial variations existed among the evaluated 15 species.
    - Exotic succulents, such as L. Deltoides, S. pachyphyllum, and S. Rubrotinctum, achieved 100% survival.
    - Contrastingly, commonly planted exotic species like S. acre had poor survival rates (40%).
2. Leaf Succulence's Role in Survival:
    - The degree of leaf succulence affects a plant's water availability during substrate water scarcity.
    - S. Rubrotinctum showcased exceptional survival due to leaf succulence, enduring without water on a lab bench for two years.
3. Significance of Leaf Succulence for Plant Selection:
    - Succulence is a vital trait in plant selection.
    - Leaf succulence's consideration in GR experiments is infrequent.
    - Evaluating leaf succulence could reshape the selection of succulents for dry climates, potentially reviving species previously disregarded due to inadequate survival in diverse climates.
4. Climate Change Implications for GR Plant Survival:
    - Plant survival becomes more crucial in south-eastern Australia due to anticipated climate changes.
    - Reduced rainfall, elevated summer temperatures, and extreme weather events are projected in future scenarios.
    - Irrigation will be essential to enhance design outcomes, environmental benefits, and plant diversity in the face of these changing conditions.

Study about Green Roof Design Techniques to Improve water use in Mediterranean conditions (Paço et al., 2019)

Lisbon, Portugal has a mild Mediterranean climate (Köppen-Gieger classification Csb/Csa), with short, mild, and rainy winters and warm to hot, dry summers. The study draws several key conclusions that shed light on optimizing the performance of GRs in various conditions.

1. The native plants under investigation were capable of enduring deficit irrigation while maintaining their aesthetic appeal on GRs. This observation suggests that incorporating indigenous plant species adapted to drought conditions could offer a practical and effective strategy for GR cultivation.
2. Moss (biocrust) roofs represent an intriguing option for cost-effective GRs in urban areas that experience dry and hot summers. They do not require irrigation and can increase the water use efficiency of other vascular plants if irrigation is needed. Mosses' ability to retain water can also help attenuate floods resulting from increased flash rain events due to climate change.
3. A pivotal role is played by water-retaining materials and substrates in GR performance, particularly in environments with limited water resources. Integrating mosses alongside vascular plants demonstrates the feasibility of establishing a more effective water management system on GRs. This insight is crucial for addressing water scarcity concerns and maximizing the ecological benefits of GRs.
4. The study signifies the feasibility of pre-cultivated blankets as a water-conserving measure in GR design. By nurturing local plants from walls and rocky environments, the potential for survival and growth on GRs becomes evident. This approach aligns with the broader trend of utilizing region-specific flora to enhance ecological sustainability within urban spaces.

Figure 42: Example test bed with Antirrhinum Linkianum, a common plant on roofs and walls of old buildings, at the rooftop of Instituto Superior de Agronomia, University of Lisbon (Paço et al., 2019).

For Green Walls

For all kinds of GWs, either interior living walls or exterior facade GWs, irrigation is necessary since rainfall cannot trap adequate water in the substrate or felt system for longer durations. Therefore, regular irrigation and nutrients are crucial for the survival and maintenance of the growing plants. Hence, it does not require complex plant selection criteria for drought conditions as is for GRs.

However, the dense foliage, higher leaf area index, substrate's water holding capacity, and lightweight, native plant species are the significant factors that should be adopted while choosing plants. Additionally, the weightage is also given to the aesthetic appearance of the plant's leaves, plant diversity, and phytoremediation properties. Lastly, the application type of GWs such as trellis, felt system, panel system, etc. requires the application of specific plant types like climber species and non-climber species.

GRIHA (Green Rating for Integrated Habitat Assessment) in association with TERI (The Energy and Resources Institute) published the list of native plant species for the Northern Plains with sub-humid soil type along with an exclusive list for the state of New Delhi which can be found in the appendix. This list gives in-depth information on the native plants and is categorized according to their traits such as shrubs with fragrant flowers, ornamental and flowering trees, rare species, exotic species, palm species, shade trees, and shrubs. This equips the reader and designer to diversify and explore further plantation options that are native and would require less maintenance than some other foreign plant species (TERI & GRIHA, 2015).

2.11 Conclusion of Findings

Following are the results summarized from the studies mentioned above. It can be concluded that the use of GRs and GWs should be considered for the new buildings as well as for the retrofit of existing buildings in hot climatic zones to reduce the heat stress on the building, resulting in lower energy consumption and cooling requirements. This would play a vital role in the construction of sustainable Net Zero Energy Buildings and Passive Buildings.

For Green Roofs

1. Leaf Area Index (LAI) and vegetation density of plants play a pivotal role in enhancing extensive GR performance in India's climate by optimizing cooling effects.
2. Water availability, substrate depth, water retention in the drainage layer, and plant selection are critical factors for plant survival on GRs. Successful GR plants are shallow-rooted, low-growing, and require minimal maintenance and nutrients.
3. The choice of substrate composition significantly influences GR performance, with water retention being crucial for thermal benefits in warm, arid climates followed by vegetation coverage, leaf area index, and substrate composition. Substrates should be porous and lightweight.

4. Key weather parameters for thermal effectiveness include solar radiation, wind speed, relative humidity, and outdoor air temperature.
5. Solar thermal shading on GRs can significantly reduce canopy and indoor air temperatures, making them an effective solution for heat mitigation.
6. GRs are most effective at reducing indoor air temperatures in hot and dry climates, with potential reductions of up to 5.1°C, and up to 9.2°C canopy air temperature in the summer season as proven in multiple studies.
7. Extensive GRs in hot-humid climate zones can achieve substantial reductions in surface temperatures, contributing to cooling strategies. Extensive GRs can create an average temperature difference of 6.2°C between internal and external surfaces.
8. Substrate depth exceeding 10 cm is optimal for GR performance in terms of temperature reduction.
9. Evapotranspiration on blue-green roofs can reach 56% to 74% of collected precipitation, increasing stormwater retention and sustaining cooling effects in hot-dry climates.
10. The use of recycled materials, such as rubber from tires, as drainage layers in GRs can lead to substantial energy savings and environmental benefits. GR with recycled rubber tires resulted in energy savings of 13% as compared to pozzolana-based GRs.
11. In semi-arid climates, vegetation on roofs is more efficient than insulation in reducing cooling loads, with insulation less commonly used in building construction due to climate conditions.
12. A time lag of 2-3 hours persists within the roofs, even after the outside temperature has cooled down.
13. Buildings with GRs significantly reduce cooling load and energy consumption compared to conventional buildings, with green envelopes providing thermal insulation. The U-value of roofs equipped with GRs, decreased from 2.13 to 0.413 W/m^2K.

For Green Walls

1. Vegetated facades significantly reduce exterior surface temperatures, indoor temperature fluctuations, and heat transfer through walls, especially during intense solar radiation.
2. In hot and humid climates (e.g., Malaysia), GW_P (panel fitted) and GW_C (climber plant or trellis type) can reduce indoor air temperatures by 4°C and 3°C respectively, whereas cavity temperatures by 8°C and 3°C respectively; although they may slightly raise temperatures behind them due to increased humidity (in the absence of natural ventilation).

3. Natural ventilation enhances thermal comfort in outdoor spaces and denser foliage could enhance performance.
4. On hot days, GW_P can lower exterior surface temperature by 0.7°C to 13.1°C, decreasing heat transfer by 2 to 33 W/m^2.
5. Passive cooling strategies involving GWs can reduce indoor temperatures by at least 5°C (e.g., UAE) during peak times and lead to 20% energy savings for cooling, primarily through blocking radiation, evaporative cooling, and plant insulation.
6. Green facades have a cooling effect, with foliage thickness affecting performance, air temperature, and humidity under the leaf layer. A foliage thickness of around 19.8 cm exhibits the best performance.
7. Buildings with GWs significantly reduce cooling load and energy consumption compared to conventional buildings, with green envelopes providing thermal insulation. The green walls decreased the U-value of walls from 2.18 to 0.23 W/m^{2}K.
8. Plant layers with dense foliage and leaves oriented parallel to walls are optimal for reducing facade surface temperatures.
9. Climber plants reduce wall deterioration, and human exposure to pollutants and can trap fine (<2.5 μm) and ultra-fine (<1 μm) particles along with SO_2 and NO_2 particles.
10. The APTI of the plants depends on their total chlorophyll content and ascorbic acid content.
11. These findings support the use of vegetated systems as effective passive cooling solutions for buildings in various climates, with potential benefits for energy efficiency and thermal comfort.

For plant selection Green Roofs

1. Native plant species adapted to drought conditions can endure deficit irrigation on GRs, offering an effective strategy. They adapt well, resist diseases, and pests, and promote biodiversity.
2. Plants having high wood density, high succulence, and small specific root lengths often result in greater survival rates in drought conditions. Herbs show a high survival rate because of water preservation through early stomatal closure. Shrubs and sub-shrubs show even higher survival rates in deep substrates as compared to herbs.
3. Moss/Biocrust roofs, not requiring irrigation, can be cost-effective in dry, urban areas, improving water use efficiency for other plants and flood attenuation.
4. Using pre-cultivated blankets with native plants from rocky environments enhances survival and ecological sustainability on GRs, aligning with regional flora trends.

5. Half-planted and fully-planted GR modules both retain approximately 82% of applied rainfall. Fully-planted modules dry out quicker and have lower leaf water status, indicating reduced plant drought stress.
6. Diverse plant species, at least five, are recommended for resilience against pests and climate. Plants with different leaf textures and water metabolism are to be preferred.
7. Spontaneous vegetation on GRs offers biodiversity benefits, and high drought survival but requires careful management.
8. Succulents have the highest survival rates. Exotic succulents like L. Deltoides, S. Pachyphyllum, and S. Rubrotinctum reported the highest chance of survival. Commonly planted exotic species like S. Acre had poor survival rates (40%) in drought conditions.
9. Leaf succulence is crucial in plant selection. Its consideration in GR experiments is infrequent. Evaluating leaf succulence could reshape succulent selection for dry climates.
10. Leaf succulence impacts water availability during substrate water scarcity. S. Rubrotinctum's exceptional survival without water highlights this trait.
11. Irrigation is essential for design outcomes, environmental benefits, and plant diversity. Consider the greening period required. A mix of annuals, herbaceous perennials, and hardy succulents for year-round greening.
12. Groundcover with limited accent plants is cost-effective.
13. Annuals need regular rainfall and may require artificial irrigation.
14. Herbaceous perennials offer aesthetics but need moisture and deep substrate.
15. Hardy succulents are extensive roof workhorses, capable of tolerating wind and drought.
16. Grasses add texture and habitat, needing deeper substrate and high maintenance.
17. Herbs require more substrate and irrigation, offering drought tolerance. Successful species are shallow-rooted, low-growing perennials, requiring minimal maintenance and nutrients.
18. Plants should establish dense root systems and resilient ground cover.
19. Consider geographic and environmental factors like temperature fluctuations and solar exposure.

Chapter 3 Interviews as Research

3.1 Current Status and Lapses

Two interviews were conducted wherein both individuals were heads of landscape design companies based in Bangalore, India, and have been practicing in the industry for 25 years. It was observed that the GW market in India is already established, however is very small. It is mainly accessed by interior designers, architects, developers, and landscape designers. However, the majority of the projects were implemented to enhance the customer or resident experience such as aesthetics, love for plants, and in some cases air pollution mitigation; without unlocking the potential these products have on the exterior of the building. The market where GWs are being used for heat stress mitigation is underway but has unfortunately negligible share in the country at the moment. GRs on the other hand is still a new product and is currently not being implemented on a wide scale.

Additionally, it was also discovered that such design offices are using self-developed internal guidelines for product installation which were independently adapted and derived from neighboring countries such as Singapore which is one of the prominent nations when it comes to implementing green building systems. The government of India or any other governmental department has not yet rolled out any exclusive guidelines for the implementation of this system, which makes it rather tough for the independent companies which then have to depend on utilizing the Test and Trial approach to improve the effectiveness of their products.

Surprisingly, research is underway in the field of vegetation study and phytoremediation which will help urban ecologists and designers to precisely choose the vegetation species according to their application and ecosystem services required. National Botanical Research Institute (CSIR-NBRI), India is currently researching to find the possible vegetation that has the potential to reduce urban heat islands and mitigate indoor air pollution.

3.2 Lessons Learned - SWOT Analysis

The interviews gave a lot of insights which point out the following strengths, weaknesses, and potentials for GRs and GWs in India:

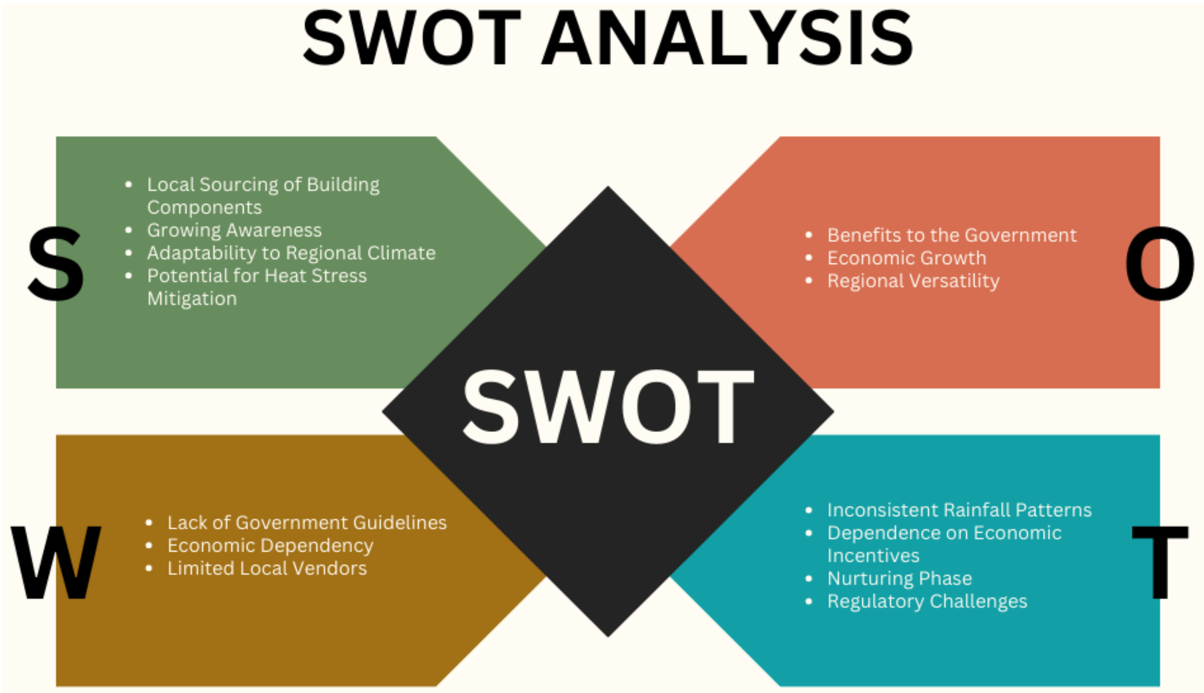

Figure 43: SWOT Analysis

Detailed SWOT Analysis from the points:

Strengths:

1. **Local Sourcing of Building Components:** Utilizing locally sourced building components can significantly reduce capital expenses, making GR and GW systems more cost-effective.
2. **Growing Awareness:** There is a growing awareness of ecosystem services provided by these systems, which can drive consumer demand and support the industry's growth.
3. **Adaptability to Regional Climate:** The adaptability of blue-green roofs and extensive GRs to varying regional climates in India offers versatility and potential for broader adoption.
4. **Potential for Heat Stress Mitigation:** GR and GW systems have substantial potential for mitigating heat stress in the Indian subcontinent, addressing a critical need in urban environments.

Weaknesses:

1. **Lack of Government Guidelines:** The absence of preset government guidelines hampers large-scale implementation, leading to the reliance on internal guidelines, which can be inconsistent and inhibitory for the industry.
2. **Economic Dependency:** The implementation of sustainable solutions often hinges on economic incentives, which can limit adoption when incentives are lacking.

3. **Limited Local Vendors:** A limited number of vendors in the industry sourcing building components and elements can create supply chain challenges and increase costs.

Opportunities:

1. **Benefits to the Government:** New Delhi faces significant challenges related to high air pollution, and the government funds air pollution control measures, including artificial water sprinkling and the establishment of air purification towers. City-wide implementation of BGS would assist in minimizing the reliance on governmental solutions. These supportive measures would not only yield immediate benefits but also contribute to the refinement and enhancement of future policies in this domain. Consequently, they could promote the adoption of GR and GW systems through the endorsement of Green Building codes like those established by IGBC and the GRIHA.
2. **Economic Growth:** Promoting awareness and knowledge about the benefits of ecosystem services offered by these systems can generate consumer demand and expand the market.
3. **Regional Versatility:** Tailoring GR and GW systems to the specific climate conditions in different Indian cities and regions can open up new opportunities for applications. For instance, regions with high air pollution can set up VGS majorly focusing on plants for phytoremediation towards air pollution.

Threats:

1. **Inconsistent Rainfall Patterns:** Variability in rainfall patterns across India poses a threat, as it may require bespoke adaptations and could limit the effectiveness of these systems in some regions.
2. **Dependence on Economic Incentives:** The reliance on economic incentives for adoption can be risky, as changes in government policies or budget constraints may affect the industry's growth.
3. **Nurturing Phase:** The use of GR and GW for heat stress mitigation strategies is still in its early stages in India, and the industry faces competition from established alternatives. Building trust and demonstrating effectiveness will be crucial.
4. **Regulatory Challenges:** The absence of government guidelines can create regulatory challenges and lead to inconsistent practices within the industry, hindering its development.

Chapter 4 Design Case - New Delhi

4.1 Introduction

New Delhi, the capital of India lies in the north of the country and has a humid subtropical hot summer climate that is mild with dry winters, hot humid summers, and moderate seasonality. During the winter months, daytime temperatures typically average around 22.5°C, dropping to an average of 8.7°C at night. In contrast, summer brings higher temperatures, with an average high of 35.7°C and an average low of 27°C. Throughout the year, there are approximately 2,856 hours of sunshine and the annual precipitation amounts to roughly 790 mm. However, due to climate change, the state as well as other parts of the country are experiencing multiplying heatwaves where the highest temperature recorded was 49°C (Gandhiok, 2022).

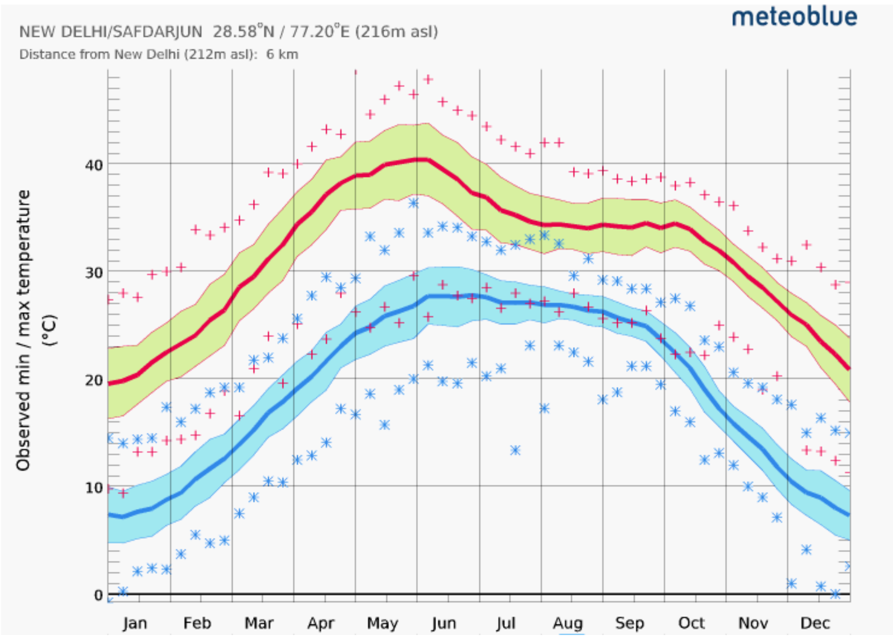

Figure 44: Observed average temperature data for New Delhi (Meteoblue.com, 2023)

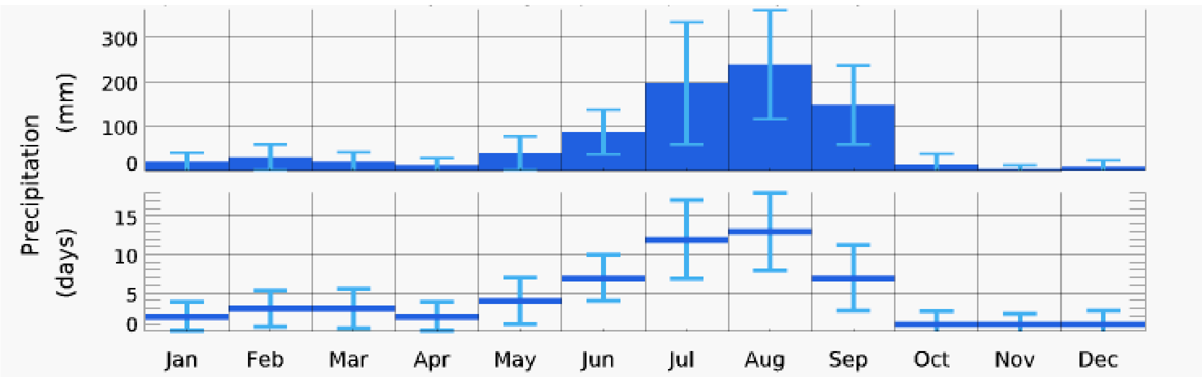

Figure 45: Observed average precipitation data for New Delhi (Meteoblue.com, 2023)

According to a report published by Energy Informatics, it was observed that air-conditioning units in the residential sector alone account for 24% of total energy consumption in India. AC units comprise 39% of the total household energy consumption in summer (Ramapragada et al., 2022). The International Energy Agency projected that by 2030, the number of ACs in India will increase to 240 million units from 27 million in 2016 (IEA, 2018). ‘An urgent climate action can secure a liveable future for all’ as said by the IPCC in its press release, calling for measures to be taken up with the highest priority. Considering these factors, it is critical to mitigate the effects of extreme heat using nature-based solutions requiring low energy consumption simultaneously with the ability to work efficiently within extreme temperature ranges.

4.2 Selection and Design of Case Study Neighborhood

New Delhi's land-use Masterplan depicts that the prevailing building typology is primarily residential, followed by public institutions such as educational campuses and office buildings. However, due to vast differences in economic demographics within residential areas, it is challenging to select a specific residential building type. A survey highlighted that one-third of Delhi's population lives in substandard housing, including 675 slums and clusters, along with 1,797 unauthorized colonies and 362 villages (Abhinav Rajput, 2021). Considering these factors, along with the following reasons, an educational institute campus is chosen as the focus of the research study:

- Campus as a Microcosm: A university campus can function as a microcosm of the broader city, providing opportunities for agile and diligent support from aspiring students.
- Scalability and Replicability: Implementing Building Greening Systems (BGS) can be initiated as pilot projects on campus, which can then be scaled or replicated in other institutional buildings.
- Challenges in Information Availability: Limited data availability online, as confirmed by interviews, makes educational campuses an ideal focus for gathering necessary information.

Moreover, the central aim of the design case is to incorporate Building Greening Systems into the structures to mitigate cooling demand. This objective is clarified by insights taken from a building simulation conducted by (Satumane et al., 2018). The efficacy of implemented BGS is contingent upon the application area. Specifically, if the building facade's area exceeds that of the roof, preference is given to GWs; conversely, if the roof area surpasses that of the facade, GRs are favored. It is important to note that this approach does not preclude the simultaneous utilization of both GRs and GWs.

Figure 46: Aerial view of the Institutional building cluster (Google Maps, 2023).

The State University of Performing and Visual Arts: The Institute of Fine Arts's existing building is selected as the design site in this study which is situated around 70 kilometers away in the outskirts of the Indian capital, New Delhi. The building is a part of 'Pandit Lakhmi Chand State University of Performing and Visual Arts' and houses the department of The Institute of Fine Arts. The building was designed by Raj Rewal Associates and was constructed in the year 2014.

The institute consists of four stories, which include classrooms, labs, sculpture and industrial design workshops, lecture and seminar halls, conference rooms, display and exhibition areas, a foundry shed, a canteen, faculty offices, and other amenities. While the ground floor hosts most major facilities and administrative areas, classrooms are situated on the upper levels. To prevent the spread of fumes, the workshops are located outside the quadrangle. At each of the four corners, the service core is topped with photovoltaic panels (Raj Rewal Associates, 2020).

Figure 47: Bird-eye view of the multi-story building (Raj Rewal Associates, 2020).

The building is designed as a play of blocks. Red Stone and Dholpur Stone cladding and grit are used for the flooring and on the facade. The stone jaalis are used for light and shadow effects in corridors.

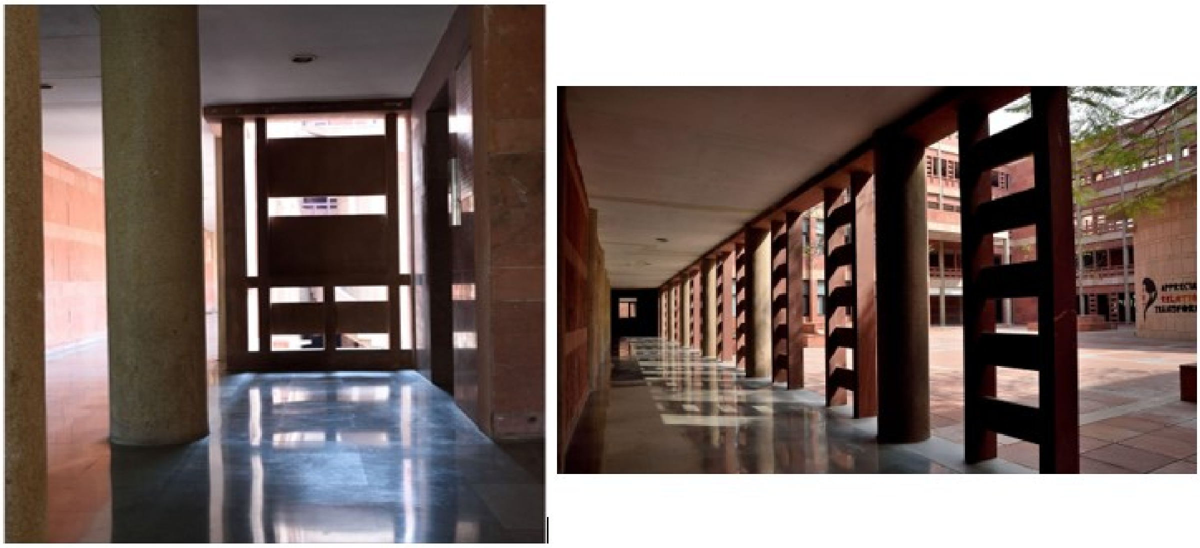

Figure 48: Inner view of the corridors and the courtyard (Raj Rewal Associates, 2020).

Passive cooling, passive daylight, and passive solar design optimize diffused sunlight in corridors and open spaces like the courtyard helping in reducing the temperature inside the building. However, GFs along with GRs might potentially reduce inside room air temperatures along with corridor air temperatures between 4 - 6.5°C.

4.3 Implementation of Green Roofs

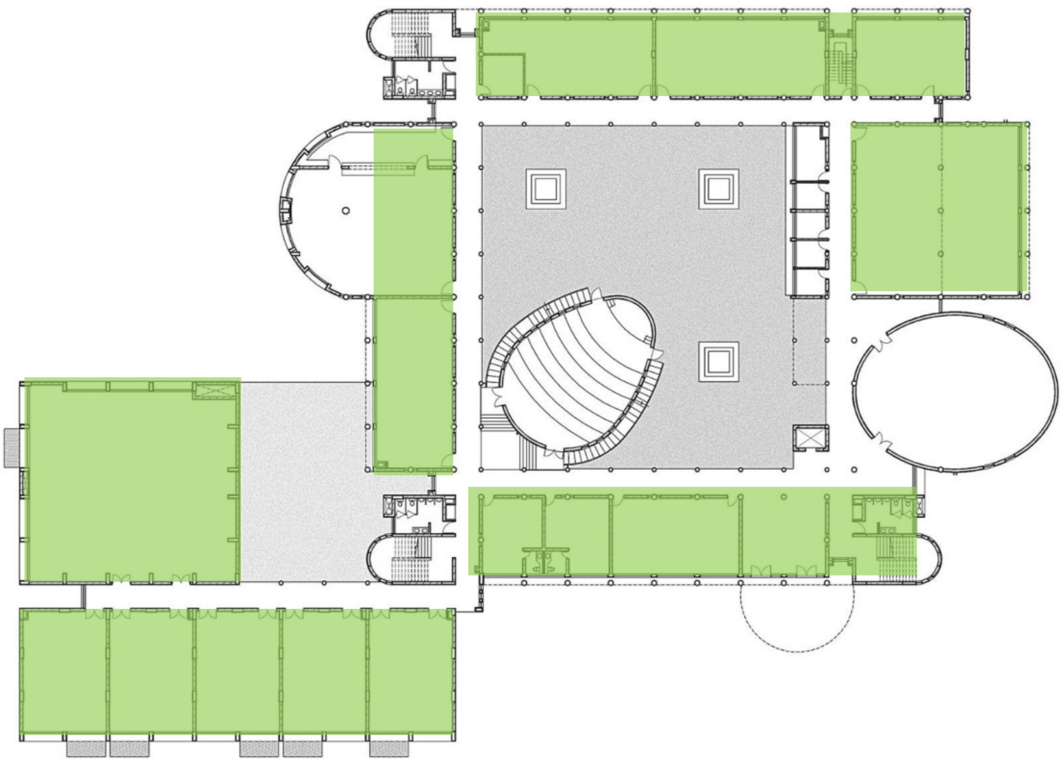

Figure 49: Building plan (Raj Rewal Associates, 2020).

Figure 47 depicts the building plan with proposed GRs highlighted in green color. The existing roof structure appears to be a typical construction where the topmost layer is a bitumen layer which is mounted on top of a brick layer to provide some insulation from high summer temperatures and prevent waterlogging. Keeping in mind the existing structure, the following design is proposed for an extensive GR with Figure 48 portraying the graphical representation and Table 1 giving the roofing layer details:

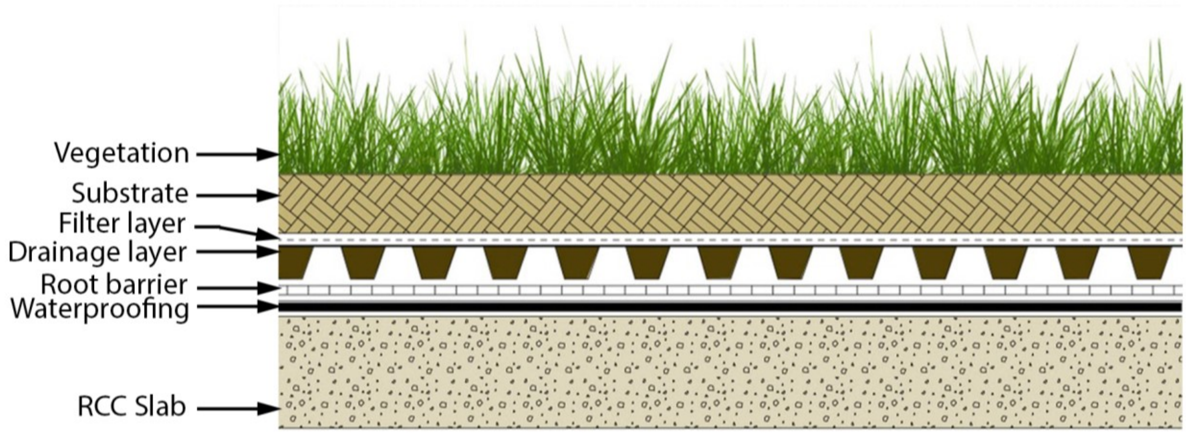

Figure 50: Designed extensive green roof details.

Layer	Thickness (mm)	Type
Slab	As per the structural details	Reinforced Cement Concrete (RCC)
Waterproofing	3	Atactic Polypropylene torch applied
Root Barrier	1	Optigrün TWB 1.0
Drainage/Retention	30	Elmich VersiDrain 30
Filter Fleece	1.1	Optigrün FIL 105
Substrate	110	Mix - 30% Perlite + 20% Vermiculite + 20% Crushed bricks + 10% Sand + 20% Cocopeat
Vegetation	50-200	Native mosses, herbs, succulents, and shrubs

Table 1: Designed Extensive Green Roof details

Deck layer: The deck layer is the bottommost layer. In this case, it is a pre-existing building therefore after the RCC slab, it would probably have brick ballast with bitumen which is prevalently used in the northern Indian region to have partial insulation properties and the usage of leftover material from brick laying.

Waterproofing layer: There are generally several options available for waterproofing membranes. However, in case of any improper applications, the water leakages might start to develop which would then affect the whole building structure. Therefore, a locally sourced 3mm Atactic Polypropylene layer is suggested for the application. This would require the waterproofing layer to be installed with the torch method ensuring proper sealing between the deck and the layer. Several vendors supplying this product in the area can be found on Indiamart (Indiamart.com, 2023). EPDM membrane is also a potential material that can be used for this layer as is currently in high demand.

Figure 51: Atactic Propylene layer with torch application (Erpenstine, 2018)

Root barrier: This layer is essential for the materials and layers beneath to prevent the further penetration of roots from the plants which is generally vigorous and might damage the layers, compromising the quality of the whole green roof installation. A soft PVC root protection membrane from Optigrün of 1 mm or similar is suggested for installation which has a density of approximately 1.29 kg/m^2 (Optigruen, 2023).

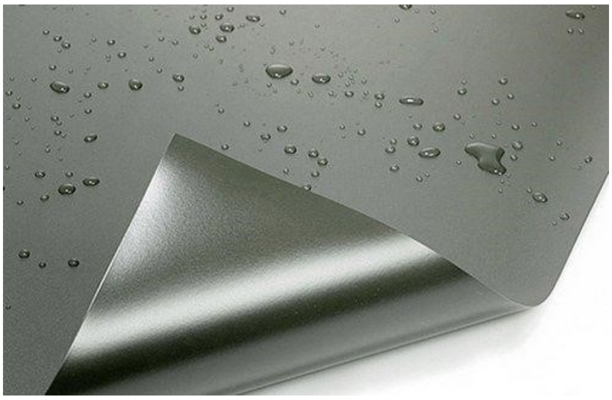

Figure 52: Root protection membrane (Optigruen, 2023).

Drainage/Retention layer: A retention layer made from PVC by Elmich, called VersiDrain 30 or similar can be used. This layer will trap and store the water after rainfall or irrigation which can be used by the plant roots for nutrients and survival during the upcoming dry days without rainfall. This layer can trap up to 11.6 l/m^2 of water for future use (Elmich, 2023).

Figure 53: VersiDrain® 30 (Elmich, 2023)

Filter layer: This layer is responsible for protecting the drainage layer from the fine particles entering from the substrate layer. The material used is generally polypropylene with a thickness of around 1 mm with a density of approx. 105 g/m^2. Optigrün's Filter Fleece FIL 105 or similar can be used which offers high puncture resistance and high vertical water permeability simultaneously (Optigruen, 2023).

Figure 54: Filter fleece FIL 105 (Optigruen, 2023).

Substrate layer: As suggested by (Vijayaraghavan & Raja, 2014), a substrate blend with 30% perlite, 20% vermiculite, 20% crushed brick, 10% sand, and 20% cocopeat on a volume basis portrayed highly favorable traits with a low bulk density of 431 kg/m^3, high water retention capacity of 39.4%. A thickness of 110 mm is preferred which allows the plant roots to have dense structure growth, increasing the chances of survival even in the times of droughts.

Vegetation: Based on the findings from multiple studies, as already discussed above, the crucial features required are as follows: Diverse plant species, around 6 different types based on their water metabolism for resilience against pest attacks and climatic fluctuations. Hardy succulents, mosses native to desert regions, native herbs, shrubs, and succulents having high leaf area index, and dense leaf foliage. Additionally, plants with shallow but dense root structures with optimum ground coverage such as the plants growing in mountainous or rocky regions can survive longer drought periods. Exotic succulents like L. Deltoides, S. Pachyphyllum, and S. Rubrotinctum can be used. Some of the plant recommendations can also be found in the appendix - Native Plant Species According to Agro-Climatic Zones.

Drain: A significant element of the GR is a drain which is responsible for evacuating excess water in times of heavy rainfall to prevent structural collapse and damage to other GR elements which might compromise the efficiency of the system. Figure 51 shows a typical drain made of galvanized steel which will be placed on top of the existing roof drain and can also be cleaned and supervised during maintenance in case of any blockage.

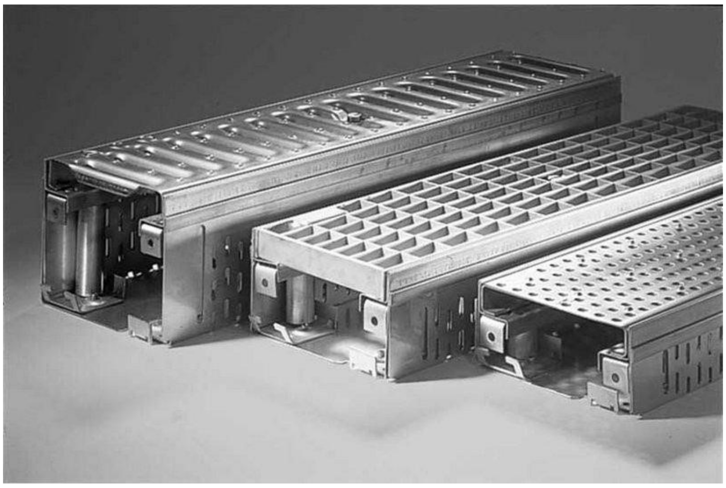

Figure 55: Drainage gutters (Optigruen, 2023).

Irrigation: An extensive GR is designed for this study where the need for artificial irrigation is considered only during the growth phase and emergency periods in case of abnormal lack of precipitation. Therefore, the major factor to keep in mind while designing this GR is that the primary source of irrigation is natural precipitation and the cooling effect is simultaneously experienced without imbalance. In case, an imbalance arises and the need for artificial irrigation is required, an automatic drip irrigation system is proposed which will irrigate the roof preferably using collected rainwater or treated greywater from the campus.

4.4 Implementation of Green Walls

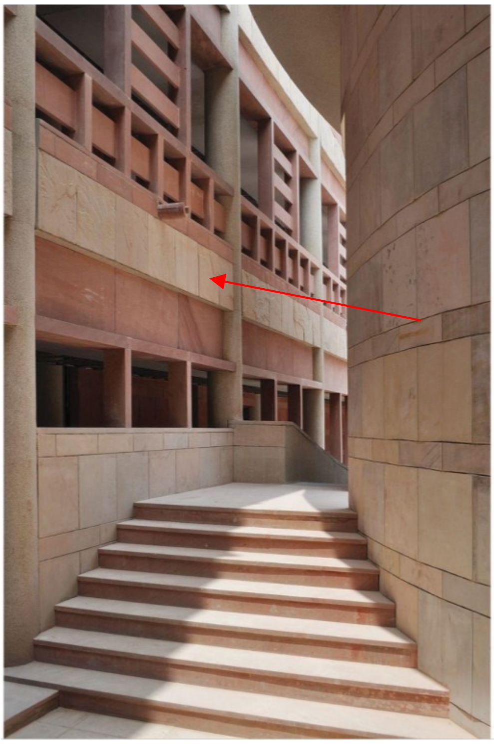

Figure 56: Irregularities on the facade (Raj Rewal Associates, 2020).

Upon closer examination, it can be seen that certain elements on the facade have irregularities and are not completely flat. This suggests that the use of a modular panel system or felt system for plant installation would be a challenging task however, not impossible in which case, the installation of an aluminum or steel structure as a base to mount the panel or felt system might be required. Climber plants on the contrary would be suitable in this scenario. This is primarily because the jaalis and block components would complement the growth of climber species similar to trellis and strengthen their hold on the facade.

Figure 57: Irregularities on the facade (Raj Rewal Associates, 2020).

Secondly, the windows on the other side of the building facade can still receive uninterrupted daylight as well as sunlight without requiring much maintenance as compared to other vertical greenery systems. Additionally, with the use of climber plants, the requirement to install a waterproofing layer is eliminated. Plant species such as Boston ivy, English ivy, or similar which are native to the region and have high leaf area index (LAI) would be suitable. There might be a need to install net or web-like structures initially to aid the growth of the plants vertically, rapidly, and in a clean manner. The open courtyard, wide corridors, and ample passive ventilation techniques would supplement the cooling effect provided by the GWs since ventilation aids in reducing the humidity caused by the evapotranspiration process by the leaves which in turn is responsible for lowering the temperature of the facade as highlighted above in this study.

Figure 58: Building facade covered with ivy plants.

One or two stages of climber plants may be installed; one into the ground directly and the other using big planter pots on the 2nd floor to ensure proper coverage if necessary. A similar example is given in the figure below, the building is now a part of the University of Hamburg, Germany.

Figure 59: Facade of a building in Hamburg, Germany covered with climber plants (Casablanca-Boutique.de, 2023)

The implementation of GRs and GWs in New Delhi, in commercial buildings, residential buildings, and other structures will greatly curb the UHI effect, in parallel to combating air pollution, resulting in better air quality, as the demand for the latter is currently high. Additional benefits achieved from these products' implementation are explored below. New Delhi in general has a very high potential for the application of these solutions, being the capital of the country, has multiple cultural centers, research centers, departmental headquarters, exhibition centers, governmental organizations, etc.

Chapter 5 Ecosystem Services

GRs and GWs are integrating increasingly into urban architecture, which offers a spectrum of ecosystem services that transform the way we interact with our built environments. These living systems, adorned with vegetation and equipped with ecological functionalities, extend beyond aesthetics. They bestow a multitude of benefits, ranging from enhanced air quality and temperature regulation to stormwater management and biodiversity support. This harmonious fusion of nature and architecture not only beautifies our cities but also redefines the urban landscape by providing a host of valuable ecological services. The diverse ecosystem services bestowed by the incorporation of GRs and GWs in buildings are as follows:

5.1 Air Pollution

Vertical Greening Systems (VGS) offer a valuable strategy for mitigating and managing air pollution in urban environments. By installing VGS on building walls, the adverse impacts of air pollution in densely populated areas can be minimized. To achieve effective air pollution reduction, the selection of air pollution-tolerant plants is crucial, as demonstrated in this study. The Air Pollution Tolerance Index (APTI) was calculated for twenty-eight climber plant species, revealing APTI values extending from 9.55 to 25.59 at an urban site and 8.10 to 23.86 at a rural site. Plants with APTI values lower than 13 are not suggested for VGS, as they are sensitive to air pollution. Likewise, plants with APTI values between 13 and 16 are not suitable for VGS in highly polluted areas but may thrive in moderately polluted regions. Conversely, tolerant plants with APTI values higher than 17 are suggested to be used in VGS. The table below shows the results and recommended list of plants. (Pandey et al., 2015).

Sr. No.	Plants	Ascorbic content	Leaf Extract pH	Total chlorophyll content	Relative Water Content (RWC)	APTI
1	Ipomoea palmata	8.77	7.79	11.25	71.58	25.59
2	Antigonon leptopus	9.45	7.58	7.37	69.39	23.98
3	Thunbergia grandiflora	8.23	6.01	11.04	66	23.46
4	Clerodendrum splendens G. Don.	8.39	5.82	10.04	71.13	23.13
5	Aristolochia elegans	7.53	5.9	10.57	70.42	22.22
6	Quisqualis indica Linn.	8.88	5.8	8.93	51.15	20.15
7	Vernonia elaeagnifolia	6.78	7.99	8.26	66.33	19.75
8	Petrea volubilis Linn.	6.54	6.23	8.97	67.45	19.21
9	Adenocalymma comosum	5.45	7.39	9.26	68.19	18.51
10	Cryptolepis buchanani Roemer	5.21	6.55	6.61	75	17.89
11	Jacquemontia violacea	5.43	6.89	8.93	62	17.32

Table 2: Climber plant species rated according to their Air Pollution Tolerance Index APTI (Pandey et al., 2015).

In the study conducted in New Belgrade, the most populous city in Serbia, measurements were taken to assess the ambient levels of PM_1, $PM_{2.5}$, and PM_{10} above a GR and a standard reference roof situated on a school building. During the evaluation in January 2020, it was observed that the GR exhibited a noteworthy reduction in particulate matter concentrations compared to the reference roof, with reductions of 7% for PM_{10}, 16.6% for $PM_{2.5}$, and 17.6% for PM_1. These findings indicate that even extensive GRs have a positive impact on air quality, specifically in terms of particulate matter concentrations, throughout the analyzed months (Kostadinović et al., 2023).

Numerous studies worldwide have been conducted and have depicted that GRs, internal and external GWs have been successful in improving the air quality of an area with particular plant species, in different mechanisms, as per the system requirements, features, and region. As learned in the interviews, New Delhi's atmosphere crucially requires the use of GR and GW for heat mitigation along with pollution mitigation in times when the $PM_{2.5}$ concentration in November 2022 was clocked at 336, which is 22 times above the safe levels set by the World Health Organisation (Ray, 2022).

5.2 Evapotranspiration

As already discussed above in the factors affecting the efficiency of GR and GW, plants generally function by absorbing CO_2 in the presence of sunlight and releasing oxygen and water in the process which is then released in the surrounding air thereby lowering the atmospheric temperature. This process of loss of water from the soil, soil surface, and the leaves of the plants is called evapotranspiration which helps in providing a cooling effect to the surroundings and plays an important role in precipitation. This ecosystem service provided by the plant is generally beneficial for outdoor conditions and is optimum for GR and GW for performance evaluation.

5.3 Thermal Comfort

Thermal comfort hinges on factors such as the ambient room temperature, humidity levels, and air circulation. However, several other variables, including physical activity, clothing, age, gender, region, and health status exert a significant influence on one's comfort. Additionally, factors like radiant heat from warm surfaces or the loss of radiant heat to cold surfaces are noteworthy considerations in achieving thermal comfort.

Plants play a crucial role in absorbing water and essential nutrients from their surroundings, transporting them between different parts of the plant, such as from leaves to roots. Some plants, like epiphytes such as English Ivy, Peace Lily, Reed Palm, Boston ferns, and Tillandsia, have an unconventional way of obtaining water by extracting it from the air rather than relying solely on their roots. These popular indoor plants serve as natural air purifiers by removing excess moisture from the atmosphere, thus helping to regulate humidity levels. An experiment in Quito, Ecuador used this principle indoors and through the use of evaporative cooling by GWs or Internal Living Walls system, was able to reduce the internal temperature and reduce the loads on the HVAC system of the building. The figure below depicts and explains the mechanism setup and its functioning. Since this system increases relative humidity indoors, a desiccant dehumidifier was used to manage the spike in humidity.

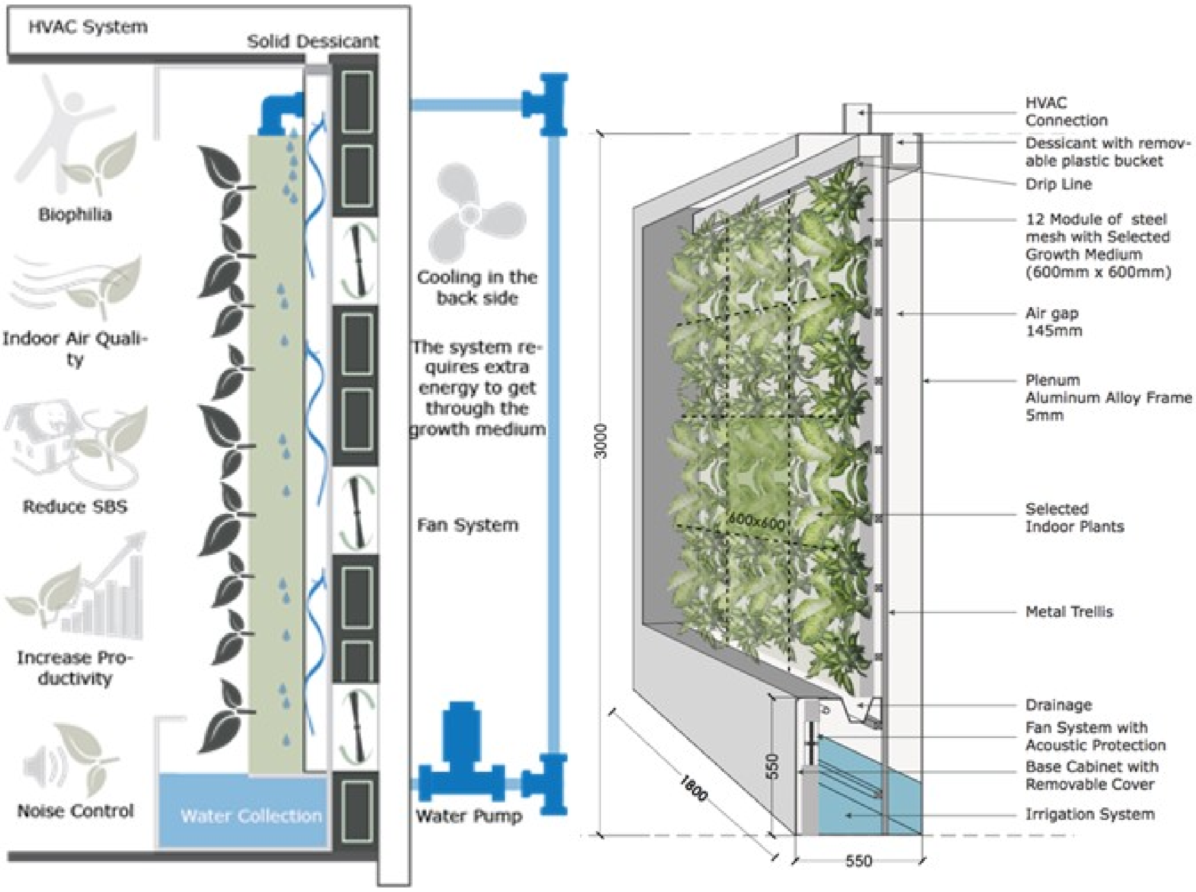

Figure 60: Living wall system design, installation, and functioning explained (Tatiana Armijos Moya et al., 2017)

5.4 Energy Reduction

The major share of energy in a building is because of heating or cooling depending on the climatic conditions. In the case of New Delhi, the cooling demand is expected to grow by 15-20% annually as said by the Chairman and Managing Director of Daikin India. With the increasing heatwaves and changing climate patterns with climate change, the demand for new air conditioners increases every 15 seconds, leading to a 435 percent rise in annual greenhouse gas emissions over the next two decades (Sinha Chaudhury, 2023).

GRs and GWs have the potential to improve building efficiency and lower electricity expenses. The growing medium within the roof's structure provides insulation, while the presence of vegetation shades the roof, leading to a reduction in both the roof as well as the facade, along with the air temperature immediately above it. A net reduction in indoor air temperatures up to 6-8 degrees Celsius can be obtained in hot regions as learned from the studies above. With the installation of an extensive GR, the U-value of roofs decreased from 2.13 to 0.413 W/m²K whereas the U-value of GWs decreased from 2.18 to 0.23 W/m²K (Pragati et al., 2023). Consequently, this reduction in temperature results in the decreased electricity demand for air conditioning during the summer months. Additionally, studies have demonstrated that green roofs' insulating properties can effectively curtail the transfer of heat from a building's exterior to its interior via the roofs and walls, a phenomenon known as heat flux. The degree of heat flux reduction depends on factors like building insulation, roof insulation, and the moisture content in the GR's soil medium. Typically, GRs can slash the air conditioning load required to cool a building by a significant 10% to 30% (US EPA, 2018).

During the winter season, a GR functions as an insulator, potentially reducing the need for heating. However, the insulating effects are less pronounced when the growing medium remains moist, which is typically the case in winter. The extent of electricity savings is contingent on various factors, including the local climate, specific building attributes, and the design and upkeep of the GR. Importantly, by diminishing the electricity demand within a building, a GR can also contribute to a reduction in the overall electricity demand on the regional power grid (US EPA, 2018).

5.5 Biodiversity

According to a Future World Report by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), there is a continuous and rapid decline in global biodiversity (Hajkowicz, 2012 as cited in Prance et al., 2014). Throughout the history of life on Earth, there have been five major extinctions and numerous minor events that caused significant and sudden decreases in biodiversity. The most recent of these, the Holocene extinction, has been predominantly driven by human activities, resulting in an ongoing reduction in biodiversity and the concurrent loss of genetic diversity. Human impact has been so substantial that the term "Anthropocene" has been coined to describe the current era, characterized by extinction rates that are 100 to 1,000 times higher than natural levels (Crutzen and Stoermer, 2000 as cited in Prance et al., 2014).

Figure 61: Extensive roof garden in Stuttgart, Germany (Optigrün, 2023).

Urban green spaces provide the opportunity to conserve native biodiversity in cities. Nonetheless, in urban areas, the complexity of vegetation is decreasing, and there is a notable absence of native vegetation and intricate understory habitats. The implementation of GRs and GWs helps resurrect the lost biodiversity in urban areas where the green spaces are now encroached upon by concrete pavements, parking lots, and multi-story buildings.

In-depth studies conducted in Switzerland and the United Kingdom have demonstrated that ecologically planned extensive GRs can offer a favorable habitat for wildlife. An effective GR designed to promote biodiversity should encompass diverse substrate depths along with the plantation of a wide array of wildflowers with sedums which are especially good for pollinators such as bees. Several insects associated with dry grasslands will find their way to an extensive GR as will nesting birds including rare or endangered species bolstering the biodiversity growth (Livingroof.org, 2016).

5.6 Well-being & Aesthetics

Having access to nature, whether through direct or indirect means, can have a positive impact on individuals' overall well-being. Stress is a significant factor in the development of chronic illnesses, and research indicates that direct exposure to nature can effectively reduce stress levels. Incorporating nature-based design elements, such as GRs and GWs, into the workplace environment can lead to reduced stress and irritability, increased productivity, and fewer instances of employee absenteeism (Hähn et al., 2021).

Figure 62: Incorporated internal living wall in office space, London (Mobilane, 2023).

The incorporation of plants into indoor constructed environments offers humans a means to reconnect with nature, yielding numerous social and economic advantages. These include enhanced performance, and satisfaction, as well as improved physical and mental well-being. The outcomes of a study performed by (Hähn et al., 2021) indicated that the introduction of plants into offices and breakout areas led to a significant increase in perceived attention, creativity, and productivity. Research conducted by Lohr et al. (1996), Raanaas et al. (2011), and Nieuwenhuis et al. (2014) as cited in (Hähn et al., 2021) demonstrated the capacity of plants to substantially restore attention and enhance the performance of individuals in office settings. Workers reported a remarkable 15% boost in creativity and productivity when plants were introduced into their work environments. These findings align with two prominent theories: Attention Restoration Theory (ART) and Stress Recovery Theory (SRT). ART elucidates how the active attention required for focused office tasks can lead to mental fatigue, while the presence of indoor plants is perceived as relaxing, thus enhancing cognitive functioning and overall well-being.

In contrast to ART, SRT places a greater emphasis on emotional and physiological processes. It proposes that exposure to natural views or interactions with nature immediately triggers an upsurge in the parasympathetic brain activity of individuals who have recently experienced stressful conditions. This heightened parasympathetic activity promotes physiological recovery and induces a state of relaxation, as suggested by (Ulrich et al., 1991 as cited in (Hähn et al., 2021).

Figure 63: WELL Certification (King, 2016).

WELL, v2.0 Certification is a rating system laid out by the International WELL Building Institute which rates a building based on criteria such as air comfort, thermal comfort, water quality, light control, acoustics, material comfort, mental health, movement comfort, etc. which promotes to improve human health and wellbeing through the built environment. The use of GRs and GWs contributes to achieving higher scores in WELL certifications, safeguarding building inhabitants' health in check.

5.7 Stormwater Management

GRs retain rainwater, allowing the moisture to evaporate from the soil and rooftop vegetation over time. As learned the study by (Dickhaut & Richter, 2023) earlier reported up to 74% evapotranspiration in the water collected in the BGR in Hamburg, Germany. This retention feature proves valuable during periods of heavy rainfall, as it helps prevent excessive runoff from overwhelming sewer systems. This, in turn, mitigates the risk of sewage overflow into local water bodies, reduces basement backups, and lowers the costs associated with treating rainwater that enters the city's combined sewer systems. Some GRs are also designed to collect rainwater for use as an alternative water supply in the future. Typically, rainwater harvested from GRs is utilized for tasks such as irrigation, toilet flushing, and other non-potable purposes (US EPA, 2018). This perfectly suits New Delhi's climate which experiences torrential monsoon rainfall in July and August which can ease off the stormwater sewers and mitigate the city from flooding as experienced in July 2023.

5.8 Acoustics

GRs and GWs are used on building facades not only for heat stress mitigation but also as noise barriers. They are effective at absorbing sound across a wide range of frequencies, primarily due to two key mechanisms: resonance resulting from the thickness of the wall structure and the quarter-wave transformer effect facilitated by the layer of plants positioned between the air and soil layers. Among various types of GWs, modular living wall systems demonstrate superior sound absorption capabilities compared to continuous living wall systems or green facades. They can achieve an absorption coefficient exceeding 0.9 within a frequency range that extends up to 600 Hertz (Attal et al., 2019). Additionally, the substrate and its moisture content can also produce a sound-damping effect. Research has verified that the level of moisture present in the soil, whether through natural means or artificial methods, significantly influences its acoustic absorption coefficient. The contrast in absorption coefficients between soil samples that are moderately dry and those that are thoroughly saturated can vary by a factor of 5 to 10 (Horoshenkov et al., 2011).

Figure 64: Green wall modules being tested for acoustics (Azkorra et al., 2015)

5.9 Heavy Metal Water Filtration

GRs can serve as a repository for a range of metals (including Ca, Mg, Al, Fe, Cr, Cu, Ni, Zn, Pb, and Cd) and counteract the acidic quality of rainwater. The use of P. grandiflora planted in GR substrate composed of cost-effective and readily available materials like perlite, vermiculite, sand, crushed brick, and coco-peat resulted in improved runoff compared to local garden soil. Runoff from the unplanted GRs appeared earlier and also comprised higher dissolved pollutant concentrations than the planted GRs. Research results (Vijayaraghavan & Joshi, 2014) indicate that GRs will contribute more ions to the roof runoff, especially during the early stages of freshly developed GRs, due to the presence of growth substrate. However, it is expected that continuous rainfall, plant uptake, and other biological activities flush the pollutants out of the system. During metal spiked rain events, P. Grandiflora planted GRs showed the potential to retain 66.6, 68.1, 15.1, 15.0, 13.0, 8.8, 16.4, and 7.7 mg of Fe, Al, Cu, Ni, Cr, Pb, Zn, and Cd, respectively, at the end of a 70-mm rainfall. Thus, the present study indicates that GRs can improve water quality. However, to achieve this, a strong emphasis is given to the choice of growth substrate which should be based on sorption ability. Therefore, the selection of plant species on GRs should not be entirely dictated by aesthetics and drought-tolerant potential, but consideration can be given to phytoremediation (Vijayaraghavan & Joshi, 2014).

5.10 Improved Efficiency of Photovoltaic Panels

Figure 65: A typical representation of PV panels installed on a Green Roof in Munich (ZinCo GmbH, 2023).

An experimental study performed in Sydney, Australia depicted that the PV modules when installed over GRs, resulted in yielding 18% higher efficiency than the PV modules installed on a standard roof. The temperature in the PV-GR module during its use, clocked a temperature high of 68.3°C in comparison to 80°C on the PV module during the same temperature conditions on a standard roof. With every 1°C rise in temperature, the conversion efficiency of PV modules decreases by 0.4% to 0.65% which also results in heating the roofs. However, when the modules are planted over a GR, the evapotranspiration due to the plants and substrate aids in reducing the temperature under the PV modules, which is further complemented by natural ventilation. These factors then bolster the efficiency of PV modules, generating more energy through lower electrical resistance. During this experiment, PV panels on GR generated up to 8.3% higher electricity than standard PV panels (Alonso-Marroquin & Qadir, 2023).

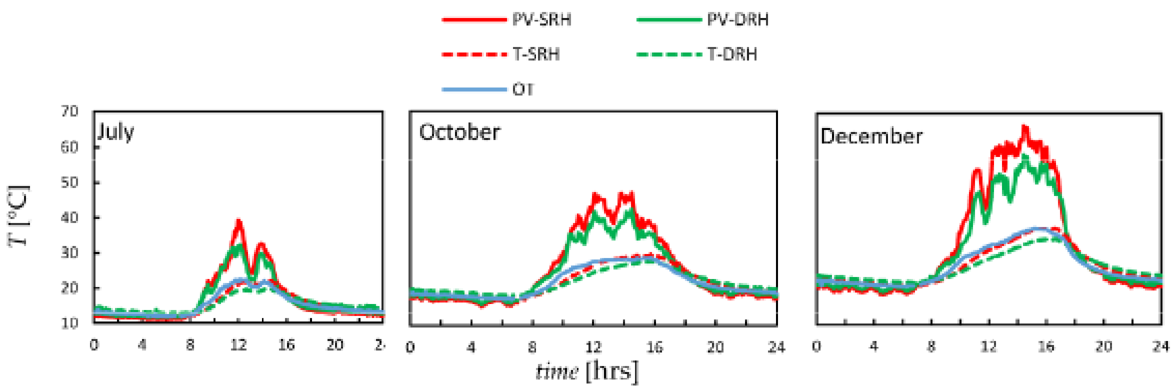

Figure 66: The temperature-to-time graph for 3 months where the red line shows the standard PV panels and the green line depicts the lower temperature in PV panels on Green Roofs (Alonso-Marroquin & Qadir, 2023).

5.11 Biofiltration

Biofiltration refers to a method employed for the elimination of air pollutants within a building exhibited by Internal GWs. This process involves directing the building's exhaust air through a biofilter, typically composed of a hydroponic living or GW containing a microbial planting medium. Within this medium, the microbes play a crucial role in transforming pollutants into less harmful substances, namely water and carbon dioxide. Subsequently, the purified air is reintroduced into the building's interior spaces through a mechanical ventilation system (Loh, 2008).

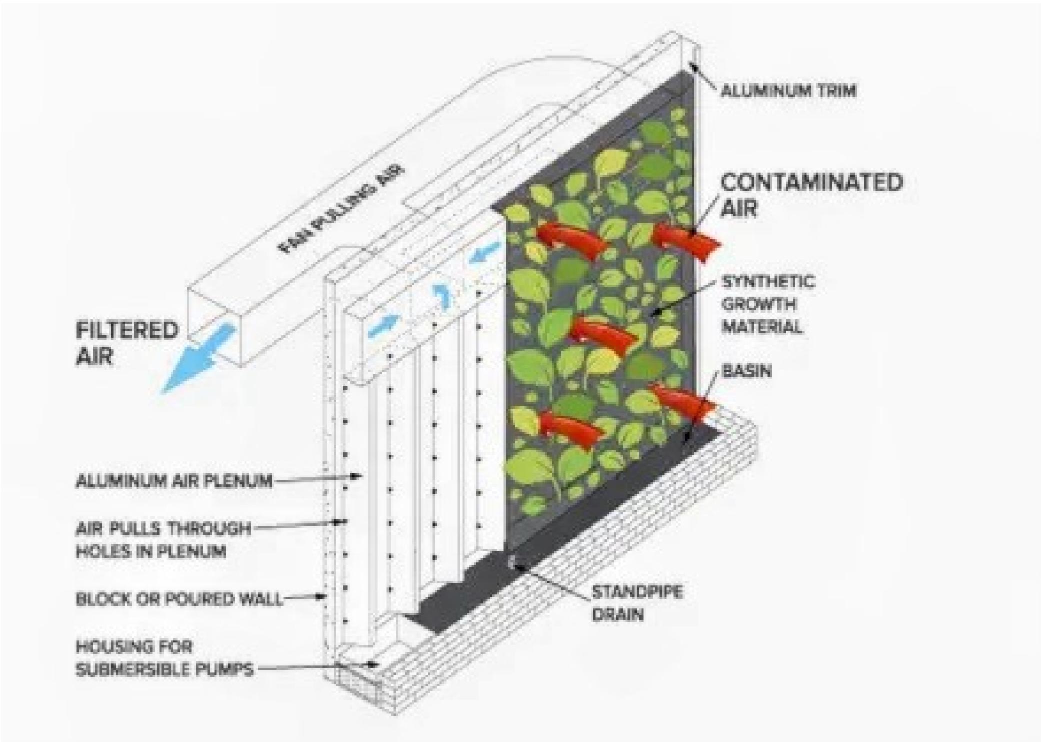

Figure 67: Biofiltration mechanism through hydroponics (Terra Landscaping, 2023)

5.12 Carbon Sequestration and Removal of Suspended Air Particles

Carbon sequestration involves extracting carbon dioxide from the air and storing it over extended durations, effectively decelerating or reversing the buildup of carbon dioxide in the planet's atmosphere. Natural mechanisms within plants facilitate the absorption of carbon dioxide from the atmosphere, subsequently storing it. It was also highlighted that in addition to carbon sequestration, expansive GFs additionally purify the air by filtering pollutants and dust, leading to cleaner air with reduced suspended air particles (Satumane et al., 2018).

5.13 Benefits from Green Building/ Certification Systems

Several Green Building Certification Systems are being used worldwide as well as in India. There are some certification systems exclusively designed by and for the Indian market such as GRIHA and IGBC. The purpose of these systems is to ensure that the designed buildings are compliant with the specified criteria such as energy efficiency, indoor environment, health wellbeing, material efficiency, water efficiency, etc. which therefore certifies how sustainable the building is. Different systems around the globe have different criteria and vary according to the purpose, type, and location of the buildings. Most of the rating systems include at least one or more criteria related to the application of GRs and/or GWs.

GRIHA (Green Rating for Integrated Habitat Assessment, India)

GRIHA which originally started in the year 2000 now offers multiple criteria which can be counted towards the building greenery system applications. The sustainable site planning section in GRIHA includes Green Infrastructure and Design to Mitigate UHI effects. Another section includes Air and Soil Pollution Control, Energy Optimization, Thermal and Acoustic Comfort, Air Quality improvement, Rainwater Management, and Visual Comfort. Summing up, with the application of BGS, up to 38% potential weightage can be achieved in a building depending upon the features and type of adopted greenery system.

Figure 68: GRIHA Rating Criterion (Rajan, 2021).

IGBC Rating System (Indian Green Building Council)

IGBC has probably the most comprehensive and dedicated rating system amongst most Green Buildings Certification Systems which ranges from Green Homes, Green Cities, Green Logistic Parks, and Green Villages to even Green Places of Worship which helps certification criteria to be curated as per the built structure. The figure below shows the variety of Rating Systems at a glance offered by IGBC.

Figure 69: GRIHA Rating Criterion (IGBC, 2023)

Like GRIHA, IGBC New Buildings also have Integrated Design Approach, Passive Architecture, Natural Vegetation, Heat Island Reduction, Rainwater Harvesting, Enhanced Energy Efficiency, Indoor and Outdoor Pollutants Mitigation, Indoor Air Quality Management, and Wastewater Reuse in its rating criteria which potentially allows to gather 28% of weightage in this particular rating system as per the scale, feature, and type of adopted greenery system.

LEED and BREEAM

Figure 70: BREEAM and LEED Certification Systems (Goeres, 2016)

LEED, which refers to Leadership in Energy and Environmental Design, is a United States-based green building rating system along with BREEAM, which refers to Building Research Establishment Environmental Assessment Method is based in the United Kingdom and is among the most widely used certification systems globally. Both systems have criteria that talk about the well-being of the building occupants, Indoor Air Quality, Energy Efficiency, Water Reuse, Urban Heat Island Reduction, and green space utilization which offer promising weightage with the use of GRs and GWs.

Chapter 6 Conclusion and Recommendations

6.1 Answer to the Research Questions

Q1. How can Green Roofs and Green Walls help in reducing heat stress in New Delhi?

This thesis research concludes that the use of building greenery systems i.e., Green Roofs and Green Walls can indisputably bring down the temperatures inside of the building as well as on the surfaces of the buildings, exhibiting a reduction in cooling loads which leads to energy savings. GRs are most effective at reducing indoor air temperatures in hot and dry climates, with potential reductions of up to 5.1°C, and canopy air temperature in the summer season up to 9.2°C. Extensive GRs can create an average temperature difference of 6.2°C between internal and external surfaces. In parallel to the GRs, GWs individually can reduce indoor air temperatures up to 5°C during peak hot climatic conditions. Building Greenery Systems majorly portrays these traits through solar radiation blockage, evapotranspiration, and plant insulation. The synergy in-situ application of both GRs and GWs in New Delhi might be able to achieve an indoor air temperature reduction of more than 5°C as exhibited by both greening systems individually. The city-wide application of BGS would surely provide a significant reduction in Urban Heat Islands, generating microclimate and increasing the thermal comfort of the residents. Detailed information about these effects can be read in Chapter 3.6 for Green Roofs and 3.7 for Green Walls.

Q2. How can Green Roofs and Green Walls be adapted to New Delhi's climate? What technical adaptations might be required for the implementation of these systems?

To adapt GRs and GWs to the climate of New Delhi, firstly, the factors on which their efficiency depends need to be evaluated along with their magnitude of dependency. Secondly, the plant selection along with substrate specifications which play a vital role in the performance of GRs and GWs needs to be explored. Thirdly, other components such as the drainage layer, apt waterproofing, structural considerations, maintenance plan, education, and training of the stakeholders will help in the adaptation of GRs and GWs to New Delhi’s context. Some factors are described below:

1. The cooling effects of GRs are attributed to evapotranspiration and are influenced by factors like solar radiation, vegetation properties, and substrate moisture.
2. Foliage thickness and Leaf Area Index (LAI) impact performance, with broader leaves reflecting and absorbing higher solar irradiance.
3. Shading by vegetation reduces surface temperatures and heat flux into buildings.
4. Thermal insulation of the substrate, dependent on its type and moisture content, affects heat flux through roofs.
5. Substrate properties like heat capacity and density impact cooling energy performance.
6. Stomatal resistance, influenced by water availability, regulates water vapor and carbon dioxide exchange, with volumetric water content inversely affecting stomatal resistance.

7. The native plant species along with local flora and fauna ensure higher survival probability and diverse plantation prevents resilience from pests.
8. Ensuring plant survival for optimum efficiency of the systems is equally important which can be achieved using plant species that can survive weather conditions such as longer drought periods. Higher leaf succulence increases the chances of plant survival.

These factors collectively contribute to the thermal performance of GRs. Tweaking these factors accordingly as per the requirements marks the adaptation of GRs and GWs to New Delhi's context. Detailed information can be read in Chapter 3.11 – Conclusion of Findings.

Moreover, as learned from the interviews, intense waterproofing strategies are not adapted widely in this region and in some cases, the building owners as well as residents fear the water leakage which can be troublesome for the well-being of the residents. Therefore, the application of good waterproof roofing technology needs to be ensured before the implementation of these systems, to prevent the compromise in product quality. Additionally, the use of locally sourced materials for the greenery systems would greatly slash the costs for installation and maintenance of the products which at the moment are considered high, hence the marginal usage.

Q3. What ecosystem services can these products provide to the surrounding environment?

Building Greening Systems offers a valuable strategy for mitigating and managing air pollution in urban environments. Green roofs were found to reduce particulate matter concentrations by 7% for PM_{10}, 16.6% for $PM_{2.5}$, and 17.6% for PM_1, emphasizing their positive impact on air quality. Evapotranspiration by plants contributes to the cooling of the surrounding atmosphere and aids in precipitation. They also enhance the thermal comfort of the residents and reduce the energy consumption of the building, reducing the cooling stress on the air conditioners as the shading effect leads to a decrease in air and room temperature. They support biodiversity, and well-being, improve concentration, lower stress levels of residents, and increments aesthetics. Stormwater management benefits from water retention during heavy rainfall, reducing the stress on the city sewers, which prevents flooding. The U-values of roofs can be decreased to 0.41 W/m^2K and walls can reduce up to 0.23 W/m^2K. GWs can effectively absorb sound across various frequencies due to resonance and the quarter-wave transformer effect providing acoustic properties. GRs can enhance the efficiency of photovoltaic panels, leading to increased energy generation. Biofiltration systems utilize living walls to purify building exhaust air. Furthermore, plants aid in carbon sequestration and the removal of suspended air particles. Various Green Building Certification Systems, like GRIHA and IGBC, promote sustainability by assessing criteria, with potential weightage of up to 38% based on the greenery systems implemented in the building. Detailed ecosystem services provided by these BGS can be read in Chapter 6 – Ecosystem Services.

6.2 Recommendations for Future Research

As shown in the factors for efficiency dependency, it is concluded that for both GRs and GWs, the substrate needs to have a fairly good amount of water-holding capacity and needs to have an apt amount of water available. This water would be absorbed by the plants which together causes evapotranspiration where the water is lost to the atmosphere, exhibiting a cooling effect for maximum efficiency. On the other hand, if we look at the precipitation data for New Delhi, the rainfall in October, November, and December is much less as compared to the whole year. The last two months of the year do not require much water because of the cold weather, hence the low evapotranspiration rates. The months of October, March, April, and May receive circa 15-18 mm of rainfall per month which is insufficient for the greenery systems to function with high efficiency. Nonetheless, there are plants and native species that were talked about in this thesis and others that do not require high amounts of water for survival but will give GRs and GWs a decent amount of functionality with less than 95% efficiency. Hence, during the design of GRs or GWs, a sweet spot needs to be established depending on the required efficiency, investment cost, water availability, irrigation type, and plant selection which can further be explored.

The prospect of using a constant irrigation source in the months of low rainfall from sources other than freshwater such as greywater or partially treated greywater can be an optimum choice to generate maximum efficiency by optimum irrigation for the building greenery systems. The usage of stored rainwater is also another viable option that can be used for artificial irrigation. In GRs, the use of mulches reduces the evaporation of water from the substrate which then provides plants with water to survive for a longer duration during no or less rainfall. On the contrary, it is a trade-off as it reduces the cooling effect of the GRs. This demands further research and experimentation in this field which can point out if the use of mulches on GRs is a suitable option. The use of recycled materials, such as rubber from tires, as drainage layers in GRs can lead to substantial energy savings and environmental benefits. Similarly, the usage of recyclable and non-recyclable materials, for instance, substrate, can be locally sourced which would not only help keep the capital and operational expenditure low but also, the carbon footprint of the greenery systems. Moreover, a building performance simulation which includes the synergy scenario of a building equipped with both GRs and GWs in New Delhi can be performed and compared to a standard reference building with the same design and materials but without GRs and GWs to see the precise number of energy savings a building would experience.

Lastly, this study provides technical information and factors responsible for the effectiveness of GRs and GWs, further research needs to be carried out in the field of urban vegetation which can explore the plant traits in-depth and form a comprehensive list of compatible flora and fauna (native or foreign species) with maintenance requirements for the use in BGS. The availability of such a list would make it convenient for architects, planners, designers, and developers to implement these strategies on a broader scale in the country.

6.3 Reflection

During the development of this thesis, certain challenges were encountered which directly or indirectly have been a deciding factor in determining the scope and development of the pathway of the study and ultimately the conclusions. The data collection distribution for this study comprises approximately 80% from secondary sources and 20% from primary sources. The access to the ground information was tough perhaps because of the lack of Search Engine Optimization or because it was not feasible to penetrate the circle which included working professionals in this very field in New Delhi who might have had more factual information than already mentioned in this study. During the interview process, multiple architecture, designers, and planning offices in India were contacted to gain insights. However, only a 4% turnout was acknowledged. Had there been more positive feedback, the domains could have been further explored, and in-depth knowledge could have been gained and worked upon.

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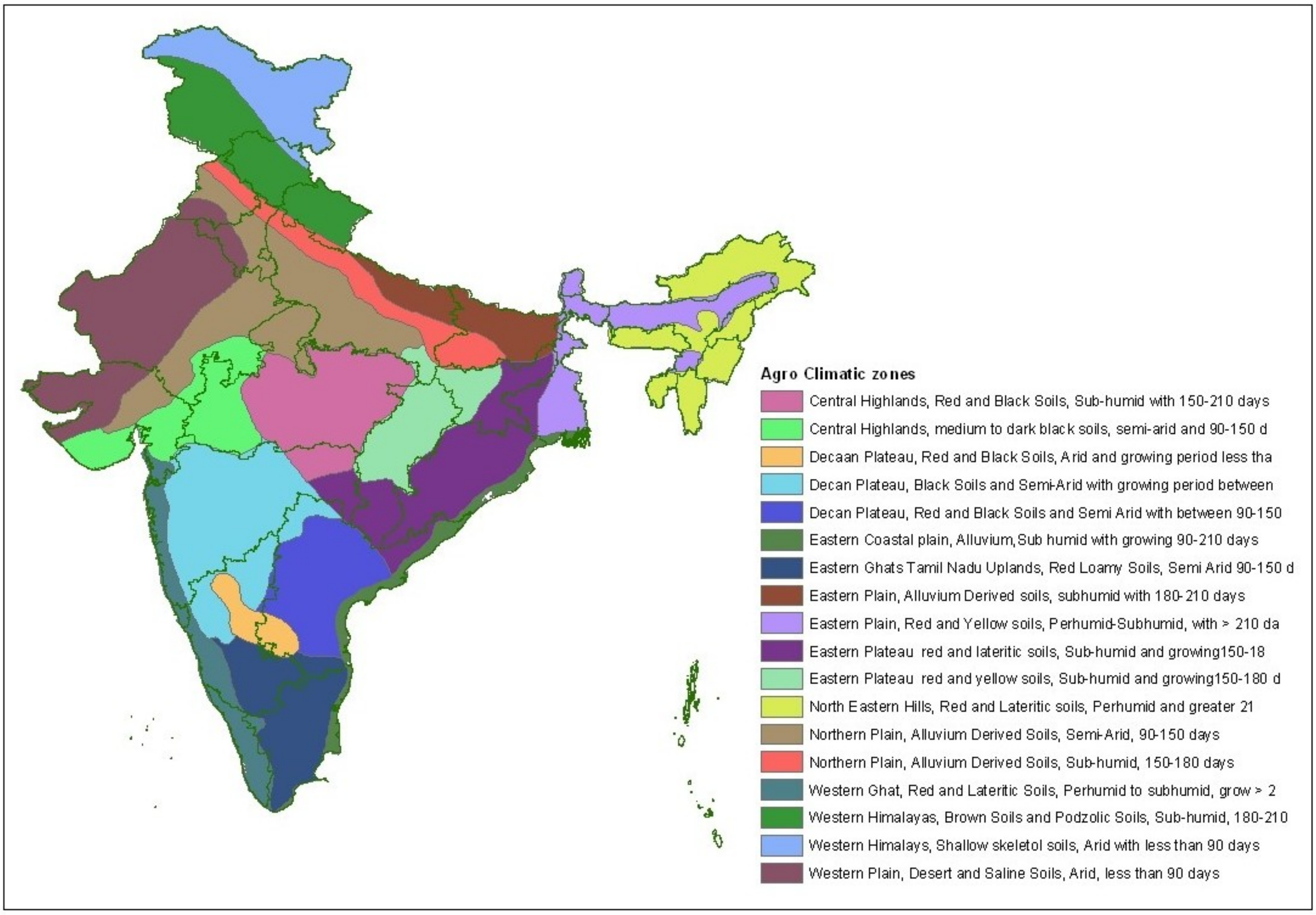
Appendix 1

Native Plant Species According to Agro-Climatic Zones

Agro-climatic zones and native species for each zone in India



Disclamer: All the native/naturalised species of flora for each agro-climatic zone/select citties of India, defined in this document is prepared from secondary sources. This list is not exhaustive and there are other tree species which will qualify as native/naturalized for respective agro climatic zone/select cities of India. Users are encouraged to explore more native/naturalised species (over and above this compiled list) suitable to the project's domain area with supporting documents.

Northern Region and North Eastern Hills

Agro-climatic zone	***North Eastern Hills* (12)**	***Northern Plain* (13)**	***Northern Plain* (14)**
Soil type	*Red and lateritic soils*	*Alluvium derived soils*	*Alluvium derived soils*
Climatic condition	*Perhumid*	*Semi-arid*	*Sub-humid*
Shrubs with fragrant flowers.	*Artabotrysodoratissimus*	*Tabernaemontana coronaria*	*Tabernaemontana coronaria*
	Magnolia grandiflora	*Hiptage madablota*	*Lawsonia alba Lam*
	Michelia champaca	*Nyctanthes arbortristis*	*Magnolia grandiflora*
	Ixora parviflora	*Gardenia florida*	*Gardenia florida*
	Mussaenda Frondosa	*G.lucida*	*G.lucida*
	Magnolia campbellii	*G. latifolia*	*G. latifolia*
	Melodorum bicolor	*Ixora parviflora*	*Ixora parviflora*
	Melodorum verrucosum	*Anthocephalus cadamba*	*Anthocephalus cadamba*
	Crataeva unilocularis	*Mimusops elengi*	*Mimusops elengi*
	Ternstroemia gymnanthera	*Murraya exotica*	*Murraya exotica*
	Saurauja nepaulensis	*Citrus aurantium*	*Citrus aurantium*
	Buddleja asiatica	*Cestrum nocturnum*	*Buddleja asiatica*
	Schizandra grandiflora	*Thevetia neriifolia*	*Clematis buchananiana*
	Popowia hookeri	*Clematis buchananiana*	*Polyalthia korinti*
	Goniothalamus sesquipedalis	*Maerua arenaria*	*Cocculus laurifolius*
	Nepenthes khasiana	*Capparis spinosa*	
	Renanthera imschootiana	*Dichrostachys cinerea*	
	Sinopodophyllum hexandrum	*Euphorbia nivulia*	
	Aquilaria khasiana		
Ornamental and flowering trees.	*Plumeria acutifolia*	*Plumeria acutifolia*	*Jacaranda mimosaefolia*
	P. rubra	*P. rubra*	*S. nilotica*
	P. alba	*P. alba*	*Cochlospermum gossypium*
	Dillenia indica	*Jacaranda mimosaefolia*	*Terminalia arjuna*
	Lagerstroemia flosreginae	*S. nilotica*	*Crataeva religiosa*

	L. thorellii	*Millingtonia hortensis*	*Lagerstroemia flosreginae*
	Amherstia nobilis	*Cochlospermum gossypium*	*L. thorellii*
	Enterolobium saman	*Cordia sebestena*	*Peltophorum inerme*
	Cassia fistula	*Terminalia arjuna*	*Cassia fistula*
	C. javanica	*Crataeva religiosa*	*C. javanica*
	Caesalpinioideae nodosa	*Lagerstroemia flosreginae*	*Caesalpinioideae nodosa*
	Enterolobium saman	*L. thorellii*	*Erythrina indica*
	Peltophorum ferrugineum	*Peltophorum inerme*	*E. Blakei*
	Saraca indica	*Butea frondosa*	*E. crista-galli*
	Poinciana regia	*Bauhinia purpurea*	*Poinciana regia*
	Mesua ferra	*B. tomentosa*	*Poinciana elata*
	Bamboo sps	*B. triandra*	*Pongamia pinnata*
	Anthocephalus cadamba	*B. variegata*	*Hibiscus collinus*
	Saraca indica	*B. acuminata*	*Kydia calycina*
	Dillenia pentagyna	*B. corymbosa*	*Chorisia speciosa*
	Garcinia xanthochymus	*B. alba*	*Ficus bengalensis*
	Kayea floribunda	*Browne coccinia*	*Moringa oleifera*
	Dipterocarpus turbinatus	*B. ariza*	*Morus alba*
	Sterculia villosa	*B. grandiceps*	*Bamboo sps*
	Sterculia colorata	*Cassia fistula*	*Bauhinia Purpurea*
	Toona ciliata	*C. javanica*	*Delonix Regia*
	Bauhinia purpurea	*Caesalpinioideae nodosa*	*Erythrina Indica*
	Bombax malabaricum	*Erythrina indica*	*Madhuca Indica*
	Wendlandia exserta	*E. Blakei*	*Dillenia aurea*
Ornamental and flowering trees.		*E. crista-galli*	*Bauhinia variegata*
		Milletia ovalifolia	*Bombax malabaricum*
		Poinciana regia	*Morinda tinctoria*
		Poinciana elata	
		Pongamia pinnata	
		Hibiscus collinus	
		Kydia calycina	
		Thespesia populnea	
		Ficus bengalensis	
		Moringa oleifera	

		Dalbergia sissoo	
		Pithecolobium dulce	
		Morus alba	
		Bamboo sps	
		Bauhinia Purpurea	
		Delonix Regia	
		Erythrina Indica	
		Sterculia villosa	
		Erythrina stricta	
		Bombax malabaricum	
		Butea monosperma	
		Leucaena leucocephala	
		Santalum album	
Trees with ornamental foliage.	*Delonix regia*	*Polyalthia longifolia*	*Polyalthia longifolia*
	Callophyllum polyanthum	*Anogeissus pendula*	*Putranjiva roxburghii*
	Vatica lanceaefolia	*Putranjiva roxburghii*	*Tamarindus indica*
	Elaeocarpus tectorius	*Tamarindus indica*	*Acacia auriculiformis*
	Elaeocarpus lanceifolius	*Acacia auriculiformis*	*Azadirachta indica*
	Elaeocarpus acuminatus	*Azadirachta indica*	*Moringa plerygosperma*
	Fagara budrunga	*Melia azedarach*	*Callistemon lanceolatus*
	Acer oblongum	*Moringa plerygosperma*	*Eucalyptus citriodora*
	Acer sikkimense	*Callistemon lanceolatus*	*Bamboo sps*
	Alnus nepalensis	*Eucalyptus citriodora*	*Schleichera Oleosa*
	Populus ciliata	*Bamboo sps*	*Soymida febrifuga*
		Adansonia digitata	*Acer laevigatum*
		Schleichera Oleosa	*Acacia catechu*
		Soymida febrifuga	*Acacia farnesiana*
		Acacia catechu	*Acacia leucophloea*
		Acacia farnesiana	*Aegle marmelos*
		Acacia leucophloea	*Aesculus indica*
		Acacia senegal	*Anogeissus latifolia*
		Acacia tortilis	*Cupressus torulosa*
		Aegle marmelos	*Dalbergia sisso*
		Dalbergia sisso	*Emblica officinalis*

		Emblica officinalis	*Populus ciliata*
		Trema politoria	*Sesbania grandiflora*
		Ziziphus jujuba	*Trema politoria*
		Buchanania lanzan	*Ziziphus jujuba*
		Boswellia serrata	*Dillenia bracteata*
		Sterculia urens	*Buchanania lanzan*
			Sapindus emarginatus
Shade trees	*Delonix regia*	*Diospyros embryopteris*	*Eugenia cuspidata*
	Tectona Grandis	*Eugenia cuspidata*	*Ficus infectoria*
	Polyalthia simiarum	*Ficus infectoria*	*F. retusa*
		F. retusa	*A.glandulosa*
		Dalbergia sissoo	*Ficus religiosa*
		Ficus religiosa	*Mangifera Indica*
		Mangifera Indica	*Cedrela toona*
		Syzygium Cumini	
Palm	*Caryota Urens*		*Borassus Flabellifer*
	Cycas pectinata		

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Deciduous Trees	Ornamental and flowering trees	Shade Trees	Shurbs
Artocarpus lacucha	*Alstonia macrophylla*	*Manikara zapota*	*Punica granatum*
Ficus drapacea	*Ficus elastica*	*Mimusops elengi*	*Carissa congesta*
Ficus benghalensis	*Ficus microcarpa*	*Madhuca longifolia*	*Ficus palmata*
Chrysophyllum oliviforme	*Ochna obtusata*	*Casesria tomentosa*	*Mallotus philippensis*
Ficus racemosa	*Prunus dulcis*	*Quercus leucotrichophora*	*Tabernaemontana sivaricata*
Suregada multiflora	*Nyctanthes arbor*	*Terminalia myricarpa*	*Euphorbia neriifolia*
Celtis tetrandra	*Annona squamosa*	*Magnolia grandiflora*	*Maytenus senegalensis*
Croton roxburghii	*Lagerstroemia speciosa*	*Michelia champaca*	*Jatropha curcas*
Ehretia acuminata	*Lagerstroemia indica*	*Syzigium cumini*	*Clerodendrum phlomidis*
Hibisceus tiliaceus	*Lagerstroemia tomentosa*	*Agathis robusta*	*Gmelina asiatica*
Holoptelea integrifolia	*Lagerstroemia floribunda*	*Syzigium nervosum*	*Platycladus orientalis*
Ziziphus mauritiana	*Neolamarckia cadamba*	*Ficus benjamina*	*Melaleuca bracteata*
Ehretia laevis	*Acacia auriculiformis*	*Ficus benghalensis*	*Capparis decidua*
Cordia dichotoma	*Psidium guajava*	*Drypetes roxburghii*	*Thevetia peruviana*
Lagerstroemia microcarpa	*Pyrus pyrifolia*	*Polyalthia longifolia*	*Balanites roxburghii*
Diospyros cordifolia	*Mangefera indica*	*Ficus lyrata*	*Tecoma castanifolia*
Pterygota alata	*Paulownia tomentosa*	*Streblus asper*	*Tecoma stans*
Bridelia retusa	*Plumeria obtusa*	*Alstonia scholaris*	*Bergera koenigii*
Atalantia monophylla	*Pterospermum acerifolium*	*Salvadora oleoides*	*Murraya paniculata*
Anogeissus pendula	*Casuarina equisetifolia*	*Eucalyptus tereticornis*	*Acacia farnesiana (rare)*
Terminalia chebula	*Cupressus sempervirens*	*Eucalyptus camaldulensis*	*Acacia tortilis*
Ficus religiosa	*Pinus roxburghii*	*Aegle marmelos*	*Prosopis juliflora*
Ficus amplissima	*Callistemo viminalis*	*Erythrina variegata*	*Parkinsonia aculeata*
Ficus virens	*Mesua ferrea*	*Sterculia foetida*	
Broussonetia papyrifera	*Bauhinia variegata*	*Tamarindus indica*	
Populus deltoides	*Bauhinia purpurea*	*Sapindus mukorossi*	
Morus alba	*Bauhinia blakeana*	*Azadirachta indica*	
Salix tetrasperma	*Butea monosperma*	*Averrhoa carambola*	
Bixa orellana	*Crataeva adansonii*	*Dalbergia lanceolaria*	
Haldina cordifolia	*Pseudobombax*	*Dalbergia sissoo*	

	ellipticum		
Gmelina arborea	*Bombax ceiba*		
Plumeria rubra	*Tabebuia aurea*		
Madhuca longifolia	*Schleichera oleosa*		
Barringtonia acutangula	*Cassia fistula*		
Phyllanthus emblica	*Senna siamea*		
Tecomella undulatta	*Cassia javanica*		
Hardwickia binata	*Millettia peguensis*		
Adansonia digitata	*Fernandoa adenophyllum*		
Ceiba pentandra	*Acacia leucophloea*		
Pongamia pinnata	*Peltophorum africanum*		
Acacia nilotica	*Enterolobium contortisiliquum*		
Acacia modesta	*Moringa oleifera*		
Acacia senegal	*Melia azedarach*		
Acacia catechu	*Millingtonia hortensis*		
Pithecellobium dulce	*Oroxylum indicum*		
Albizia lebbeck			
Leucaena leucocephala			

Trees that require more water	**Exotic species**	**Rare Trees in Delhi**	**Palm**
Diospyros malabarica	*Wrightia tinctoria*	*Guazuma ulmifolia*	*Caryota urens*
Manilkara hexandra	*Kigelia africana*	*Flacourtia indica*	*Roystonea regia*
Afrocarpus gracilior	*Grevillea robusta*	*Prunus persica*	*Phoenix sylvestris (rare)*
	Spathodea campanulata	*Anogeissus acuminata*	*Phoenix roebelinii (rare)*
	Albizia procera	*Cinnamomum camphora*	*Phoenix rupicola (exotic)*
	Albizia lucidior	*Salvadora persica*	*Dypsis lutescens*
	Adenanthera microsperma	*Reutealis trisperma*	*Livistona chinensis*
		Thespesia populnea	*Washingtonia filifera (rare)*
		Gynocardia odorata (only one tree)	*Sabal mauritiiformis (rare)*
		Trewia nudiflora	*Livistona rotundifolia*
		Sapium sebiferum	*Sabal palmetto*
		Artocarpus heterophyllus	
		Cordia gharaf	
		Erythroxylum coca	

		Mitragyna parviflora	
		Tectona grandis	
		Terminalia muelleri	
		Aleurites moluccana	
		Platanus orientalis	
		Pterospermum xylocarpum	
		Liquidambar formosana	
		Juniperus chinensis	
		Brachychiton gregorii	
		Ficus binnendijikii	
		Olea europaea	
		Bischofia javanica	
		Desmodium oojeinense	
		Crescentia alata	
		Erythrina blakei	
		Erythrina suberosa	
		Joannesia princeps	
		Swietenia mahagoni	
		Saraca asoca	
		Cassia grandis	
		Senna surattensis	
		Chukrasia tabularis	
		Cassia roxburghii	
		Senna spectabilis	
		Cassia renigera	
		Markhamia lutea	
		Calpurnia aurea	
		Spondias pinnata	
		Gliricidia sepium	
		Prosopis cineraria	
		Prosopis glandulosa	
		Paraserianthes falcataria	
		Caesalpinia ferrea	
		Parkia biglandulosa	
		Acrocarpus fraxinifolius	