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Review

Comprehensive Assessment of the Impact of Green Roofs and Walls on Building Energy Performance: A Scientific Review

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Abstract: Sustainability and energy efficiency are now two pivotal goals that society aims towards. Green roofs and facades have gained significant attention in this direction for innovative, sustainable solutions for enhancing building energy performance. With a focus on sustainable urban development and energy-efficient building practices, this study delves into the intricate relationship between these green infrastructure elements and the overall energy dynamics of constructed environments. Furthermore, a range of case studies from diverse geographical locations are presented to provide valuable insights into their practical implications as emerging technologies that contribute to improved insulation, reduced heat transfer, regulating indoor temperatures, and mitigation of urban heat island effects, thus reducing the need for artificial heating and cooling and optimizing overall energy consumption. This comprehensive review serves as a dataset for understanding and highlighting all the research findings of the numerical and experimental investigations invested in the field of greenery systems to encourage their integration, which is crucial for combating climate change and pollution. Previous research is often focused on isolated, short-term, or single-climate analyses of consumption; therefore, by providing an inclusive description of their practical benefits in both temperate and extreme climates, the gap in previous articles is tackled.

Keywords: eco-envelopes; numerical simulation; building insulation; environmental benefits; cooling effect; energy efficiency; climate mitigation

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1. Introduction

Today, most of the global population resides in urban areas, and there is an increasing inclination towards city living with each passing year. The latest United Nations report shows that the urban population will rise to 67% by 2050 [1]. In many countries worldwide, climate change and the depletion of natural energy resources are currently topics of interest [2]. Moreover, cities continuously grow and expand their peripheries to accommodate the increasing population from rural migration to urban areas. A recent report by the United Nations indicated that it is estimated that urbanization in developed countries will reach 83% by the year 2030 if the trend keeps advancing [3–5]. This in return will lead to numerous environmental problems on a local and global scale, such as increased greenhouse gas emissions. With this exponential increase in global urbanization over the last four decades, there has been a call for new buildings, energy, and resources such as water and land. In another one of its reports, the United Nations Environment Programme estimated that constructing and maintaining buildings account for around

40% of global primary energy demand, and buildings are responsible for 33% of global greenhouse gas emissions. Urban areas house over 55% of the worldwide population. This percentage is foreseen to rise to nearly 70% by 2050, which causes risks from climate change due to dense populations, extensive rigid surfaces, and limited green spaces. One of the most compelling resulting challenges is the urban heat island (UHI) effect, which causes cities' temperatures to be 1–3 °C warmer than surrounding rural areas, with this difference reaching up to 12 °C during heat waves. The extensive presence of buildings leads to up to 70% of rainfall becoming surface runoff, intensifying the risk of flooding. Not only that, the frequency of extreme precipitation events is expected to increase by up to 40%, and sea-level rise is projected to reach 0.5 to 1 m by the end of the century. In this context, in urban areas, effective adaptation strategies, such as green infrastructure, are being called for. Whether green roofs, walls, or urban vegetation, these not only mitigate the UHI effect by reducing ambient temperatures by up to 5 °C, but they also provide natural shading and cooling, lowering energy demands for air-conditioning. The vegetation and permeable surfaces notably enhance stormwater management, absorbing rainfall, reducing runoff, and preventing flooding. For example, green roofs can retain up to 80% of annual rainfall, relieving pressure on urban drainage systems. Likewise, green infrastructure improves air quality by filtering pollutants and absorbing CO_2. Air pollution contributes to 7 million premature deaths annually, which is attributed to poor air quality. Thus, the enhancement of natural processes offered by green infrastructure not only mitigates the impacts of climate change but also improves overall urban resilience and livability, making it a key strategy in sustainable urban planning [6–9].

The present global energy consumption data underscore the urgent need for significant interventions to reduce the building sector's proportion of overall worldwide energy usage. Notably, projections indicate that unless timely measures are implemented to enhance buildings' energy efficiency (BEE), the energy consumption in buildings in China could surge to 40% of the total energy consumption in the foreseeable future. Within this context, the enhancement of BEE is anticipated to play a pivotal role in curbing energy consumption, contributing to environmental preservation and fostering social and economic development. Key strategies to bolster BEE can be categorized into five areas: (a) enhancement of energy codes for new constructions, (b) implementation of energy labeling and rating systems for buildings, (c) adoption of heat metering and energy-efficient retrofits, (d) promotion of the use of renewable energy sources in buildings, and (e) monitoring the energy efficiency of large public structures [10,11]. In European nations, specific directives target the energy consumption of buildings, exemplified by the Energy Performance of Buildings Directives (EPBDs) 2002/91/EC and 2010/31/EC. According to these directives, member states individually assess and certify existing buildings. These initiatives introduced the nearly zero-energy buildings (NZEBs) concept, advocating for low energy requirements and integrating renewable energy sources [12]. Recently, in the United Kingdom (UK) and other European Union (EU) countries, new regulations that advocate for net zero-carbon buildings have been and are being adopted, aiming to reduce the environmental impacts of energy use in homes [13,14]. By implementing green building design, environmentally conscious construction is anticipated to reduce carbon emissions and minimize the consumption of natural resources by incorporating energy-saving measures and promoting the use of recyclable and sustainable materials [11,15–17].

Green buildings are versatile structures that encompass various methods of integrating renewable energy solutions into architectural concepts, incorporating greenery systems, careful material selection, and strategic site planning [18]. The influence of sustainable building envelope technologies on the design and construction of more environmentally friendly buildings, building components, and urban spaces is undeniable, and their implementation leads to the realization of low-energy buildings [7]. Green buildings are perceived as a comprehensive and crucial remedy to decrease energy consumption within the construction industry and curbing greenhouse gas emissions. This is achieved by effectively utilizing and managing energy transfer from the building envelope [19].

Incorporating greenery systems on building surfaces regulates structures' microclimatic conditions without excessive energy consumption [20]. As per survey results obtained in the United States of America (USA) [17], green buildings consume roughly 30% less energy than traditional buildings. Many standards are linked to the concept of green buildings and efficient energy use in buildings, such as the Building Research Establishment Environmental Assessment Methodology (BREEAM) in the United Kingdom, the Leadership in Energy and Environmental Design (LEED) in the United States of America, and the Green Building Label (GBL) in China [21]. Many parameters are included within these standards, such as pollution, waste, energy, health and well-being, water, and ecology [14]. These green systems incorporated into buildings mainly cover green roofs (GRs) and walls encompassing stationary and moving facades. One of the most critical components in a building is its roof, which makes up almost 20–25% of the building's total surface area. Green roofs are roof systems with different plant species on a growth substrate. Consequently, an efficiently designed and integrated green roof has shown great potential to positively impact buildings and urban environments, as it replaces lost green spaces and habitats in modern cities [7]. A vertical greenery system is broken down into facades, walls, blind walls, and partition walls; however, the primary intention is to grow plants on the walls of buildings. This system can also be termed green wall, vertical green, vertical garden, and biowall. The green wall consists of a green facade and a living wall. The vegetation that grows over the building envelope is the main difference between green facades and living walls. A green facade typically involves intertwining climbing vegetation within a structural framework composed of mesh, wires, or cables.

Conversely, living walls commonly incorporate potted plants, as opposed to climbing vegetation. The widening environmental awareness leads to the exploitation of these systems for their practical ability to enhance building performance in terms of efficient energy use, desirable outdoor and indoor environments, and air quality [20,22,23]. From this point of view, it could be validated that integrating these greenery systems into the buildings in urban areas has prodigious potential to foster the quality of the urban environment by providing improved water and air quality, a decline in carbon emissions and temperature, and depreciation of heat island effects, as well as stormwater management [24–26]. In addition to their profound environmental impact, they provide additional benefits to the public in social and economic respects. Their presence has a significant psychological effect on urban dwellers, enhances the cities' visual aesthetics, and raises real estate prices [23,27]. Most importantly, greenery systems can be devised as a passive design solution, providing additional benefits, such as insulating winter impact and shading in summer [11,20,23]. In recent years, the number of studies on green roofs and/or facades has been increasing, and several reviews have been published in an attempt to summarize and organize the scientific knowledge on this topic. Saadatian et al. [16] focused on energy-related matters and prospects offered by green roofs. Berardi et al. [28] presented state-of-the-art GRs, emphasizing current implementations, technologies, and benefits. In their article, the authors presented the profits related to building energy consumption reduction, sound insulation increase, water management, urban heat island effect mitigation, air pollution abatement [29], and ecological preservation. Under the energy conservation umbrella, Hashemi et al. [30] reviewed the effects of applying a GR strategy in the reduction in energy consumption and quality of runoff water. Moreover, Raji et al. [1] presented an overview of the impact of greening systems on temperature, heat flux, and HVAC systems, which contribute to building energy performance. In their review, Safikhani et al. [20] discussed the benefits of vertical greenery systems in temperature reduction and their cooling effects, contributing to their energy reduction advantages. Also, Besir et al. [11] carried out a comprehensive review of the energy-saving features of greenery systems that covered many branches, such as evapotranspiration, shading effect, cooling demand minimization, and wind blockage impact. The impacts of greenery systems on human health were considered within the scope of their study. These previous studies mainly focused on reviewing the performance and benefits without describing the technologies, materials, and numerical simulations that assess and validate the thermal benefits of these greenery systems. This review addresses two critical global challenges: energy efficiency in buildings and climate change mitigation. Buildings contribute significantly to global energy consumption, primarily for heating and cooling, and this paper emphasizes how green roofs and facades can serve as sustainable solutions to reduce this demand. By mitigating the urban heat island effect and lowering greenhouse gas emissions, green infrastructure aligns with broader climate action goals. Additionally, this paper fills a crucial gap in current research by providing a comprehensive analysis of green infrastructure's long-term energy benefits in both temperate and extreme climates, surpassing the limited scope of earlier studies. Previous studies mainly focused on reviewing the performance and benefits without describing the technologies, materials, and numerical simulations that assess and validate the thermal benefits of these greenery systems. Distinguished from prior reviews on green roofs and facades, this paper seeks to critically examine the experimental and numerical investigations performed on these greenery systems, targeting their thermal and energy conservation purposes and collating work and research invested in this domain. Through an extensive assessment and review of numerical and experimental investigations, this work synthesizes a dataset that not only highlights the practical advantages of green roofs and facades, such as enhanced insulation, reduced heat transfer, and improved indoor temperatures, but also compiles all the studies found to date in one place, facilitating research. By presenting case studies from diverse geographical locations, this article underscores the potential of these technologies for sustainable urban development. Ultimately, this review promotes the broader integration of green infrastructure into building practices, encouraging a shift towards energy-efficient, sustainable urban environments that contribute to global efforts to combat climate change.

2. Historical Context

According to existing research, passive cooling techniques such as covering a structure's rooftop with soil, moistening the soil, and shadowing the wet soil's surface have been employed across ages in many nations, with benefits verified in varying climatic circumstances and building attributes [30]. Dating back to the fifth century (500 BC), one of the most famous ancient green roofs was constructed in the Hanging Gardens of Babylon and is acknowledged as the earliest example of a greenery system [11,24,31]. The ziggurat, a pyramidal stepped temple tower of ancient Mesopotamia, also utilized living roofs. Just like Babylon, the Romans and Greeks used GRs in their architecture during their time. For instance, the Mysteries Villa shows such integration and provides an example of a space that enriches human activities while boosting aesthetic value and roof life. Germany is the world leader in employing this strategy, as green roofs are being designed, developed, and implemented on a large scale. In this context, the first comprehensive program was implemented in the early 20th century by retrofitting houses with greenery surfaces [7]. This has led to an annual increase in green roof coverage in Germany, reaching about 13.5 million square meters, which is remarkable. In other words, 10% of the houses located in Germany can be considered green buildings as of now [11,16,24,32]. In 2015, in Germany, the total value of greenery surfaces, specifically GRs, was estimated to be worth EUR 254 million [23,33]. Over the last couple of years, developed countries such as the United States of America (USA), Canada, Singapore, Japan, and Australia have summoned novel standards to ensure an energy-efficient and cost-effective retrofitting of existing buildings and newly built ones with greenery systems. As a result, 15% of the roofs in Switzerland have been covered by green roofs, yielding 4 GW/year in energy savings [34]. On the other side of the world, in Canada, a similar regulation has been put in place that mandates green roofs occupy between 20% and 60% of the roof area when a building's floor area exceeds 2000 m^2. In Japan, private buildings with a floor area greater than 1000 m^2 and public buildings with a floor area surpassing 200 m^2 are obliged to have plants occupying at least 20% of their roof area [11,35]. Contemporary green roofs draw inspiration from ancient methods, but technological progress has significantly enhanced their efficiency, practicality, and overall benefits compared to their historical counterparts. The widespread adoption of green roofs began in Germany during the early 1960s in response to emerging energy crises [32]. Extensive research has focused on biodiversity, substrate, roof construction, and design guidelines. The popularity of GRs also expanded to Austria, Switzerland, and the United Kingdom (UK) during the same period [7].

Dating back to around 2000 years ago, in the Mediterranean region, vertical gardens with different types of plants, mainly vines, were employed in the narrow backyards of palaces and on building envelopes to prevent excessive sunlight in the summertime and to provide more relaxed and comfortable indoor conditions for occupants. Also, these vines provided shade for the facades, ensured by evapotranspiration cooling, and had economic value, as all the fruits could be used. Half a millennium ago, in Central Europe, prevalent climbing plants in castles and villages were woody vines. Fruit espaliers and ornamental climbing roses were also widely embraced. As shown in Figure 1, adorning vertical spaces with summer flowers reminiscent of Bavaria's balcony tradition was a trend in rural settings. Moreover, as cities expanded during industrialization, vertical gardens, mainly adorned with climbing plants, gained popularity on terraces and balconies [7,36]. As time progressed, during the 17th and 18th centuries, climbing plants became popular, and their usage greatly increased in the United Kingdom and Central Europe. During the 19th century, in cities across Europe and North America, residents in urban areas were primarily drawn to ornamental features, making woody climbers the prevalent choice for green surfaces on buildings. Botanical environments influenced efforts to develop living wall systems, particularly those rich in biodiversity [11,23,24]. In Germany, the impetus for a transformative approach to more environmentally sustainable buildings emerged in the late 1970s, primarily influenced by artists like Hundertwasser. Architects and planners embraced this concept, shifting from developing new settlements on the outskirts to promoting inner-city reconstruction. Incentive programs to support this paradigm shift were initiated in the early 1980s. Berlin was a focal point for these progressive ideas, with the city's wall redirecting attention toward urban redevelopment projects. Green facades, a less obvious yet integral aspect of urban design, gained popularity during this period. Recognizing the relative ease of constructing green facades, Berlin implemented an incentive program to encourage their adoption [36]. From the 1980s to the end of the 1990s, which covers the duration of the program, approximately 246 square meters of greenery were incorporated into the facades of buildings in Berlin [11,37]. Even though there was a consensus among urban people that these greenery systems were incompatible with modern architecture due to the difficulties in retrofitting, technological developments led to rising comfort levels for occupants and social awareness of environmental issues. All these factors promoted greenery systems, which are now the center of interest year after year.

Figure 1. Bavaria's balcony tradition [38].

3. Green Roofs

3.1. Green Roof Introduction

Green roof (GR) systems have been established as an essential nature-based construction strategy in all parts of the world. Also known as eco-roofs, living roofs, and roof gardens, they involve introducing plants or seeds that grow in a medium on a rooftop, or in other words, are roofs coated with green vegetation and growing medium [24,39]. This simple concept has become one of the leading high-tech solutions to tackle all the technical requirements demanded by the building sector, as they convert the impervious, rigid areas of a rooftop into multifunctional spaces using growing media and vegetation and are being widely used for recreating spaces, especially in urban areas [40–42]. GRs can benefit urban regions in terms of aesthetic and environmental aspects by reducing greenhouse gas emissions and urban heat island effects in densely populated areas [43,44], reducing air pollution, and preventing acid rain by escalating pH values [40]. They enhance city water quality and minimize flooding risks, as they retain the excess water, provide better ecological habitats for urban life and wildlife, and absorb regional noise pollution within metropolitan areas [41,42,45,46]. Another benefit of green roofs is that they enhance architectural interest and biodiversity[47]. Moving on to the key roles of green roofs in buildings, they target energy saving, thermal insulation, shading, and evapotranspiration, which significantly augments the overall thermal performance of buildings and the indoor conditions and temperatures [48]. During the summer season, the application of green roofs can lead to a reduction in heat flow through the building roof by around 80%. Consequently, there is a decrease in annual energy consumption due to the minor temperature differential between indoor and outdoor air [11,42,46]. The green roof design is based on several components, and layers listed below from top to bottom are shown in Figure 2 [7,11,24,45,49].

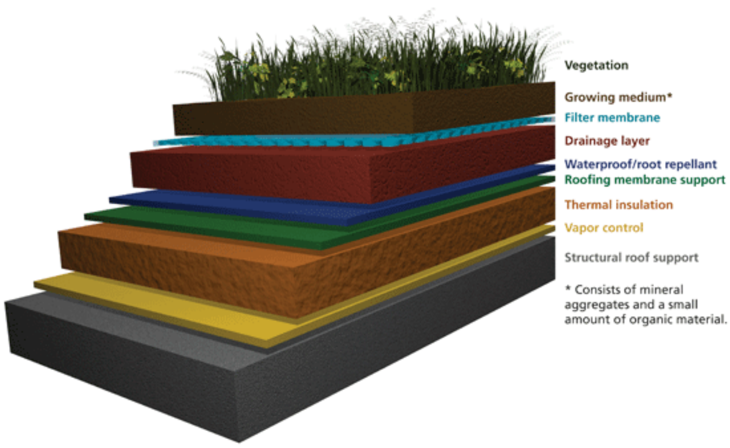

Figure 2. Green roof layers [50].

- Vegetation, the topmost layer, is where various plants and vegetation are planted. The success of a green roof is linked to how healthy the plantations are. Its benefits heavily depend on the chosen plant species, as they boost water and air quality and thermal performance by reducing heat through the process of evapotranspiration. This process involves the transfer of water from the soil and plants to the atmosphere, combining both evaporation and transpiration. Evapotranspiration actively cools the surrounding environment, as heat energy is used to convert liquid water into vapor, reducing the ambient temperature. Research has shown that this cooling phenomenon can lower the surface temperatures by up to 30–40 °C on green roofs and reduce ambient air temperatures by up to 5 °C. By mitigating the urban heat island effect and reducing reliance on air-conditioning, the vegetation layer contributes significantly to energy savings and enhances the overall thermal comfort of metropolitan areas. Not only does the vegetation contribute to the visual appearance of the green roof, but it also prevents substrate erosion and protects diverse animal species, notably arthropods and birds. When selecting vegetation, it is essential to consider climate conditions, including factors such as rainfall intensity, humidity, wind, and solar radiation. Since extensive green roofs are the most common, its associated plants are shallow and drought-tolerant; thus, they are best suited to temperate, Mediterranean, and semi-arid climates, since plants like sedums, succulents, and grasses can thrive with minimal water, handle moderate temperature fluctuations, and survive occasional droughts. Extensive green roofs perform well in moderate humid conditions ranging from 30% to 60%. The characteristics of the substrate's mixture in terms of pH, salinity, and nutrients are also directly linked to the choice of plants. Recently, many efforts have been put into identifying appropriate plant species tailored to specific soil depths. Since extensive green roofs are more commonly installed, the categorization of plant species for them is outlined as follows.

  - For depths between 0–5 cm, sedum, mosses, and lichens are recommended.
  - Within the 5–10 cm range, optimal choices include short-wildflower meadows, long-growing, drought-tolerant perennials, grasses, alpines, and small bulbs.
  - Ranging from 10–20 cm, a blend of low or medium perennials, grasses, bulbs, and annuals adapted to dry habitats, along with wildflowers and hardy subshrubs, is preferred.

- The growing medium, or the substrate layer, is designed to retain water, give nutrients, and provide optimum aeration for plant roots needed to ensure their biological functions' well-being. In addition, it offers space for the roots to grip and strengthen to overcome the wind force and other rough climatic conditions on the rooftops. Soil is the most used natural growing medium. The thickness and mass of the substrate are liable to the type of vegetation, roof structure, prevailing climatic conditions, and the chosen irrigation approach. During rainfall, specific substrates, like soil that contains clay and other organic particles, experience rapid saturation, increasing their weight. Typically, the substrate weight ranges between 12–14 kg/m^2 and 600 kg/m^2, with an 8 cm thickness for extensive green roofs and a 50–60 cm thickness for intensive green roofs. A substrate that is 5–15 cm deep supports a range of plants in regions with 600–1200 mm of annual rainfall. In high-humidity areas, substrates are designed to handle higher moisture; therefore, water-retentive substrates are used, with moisture content around 30–60% by volume, while in low-humidity areas, regions with less than 250 mm of annual rainfall, substrates act on moisture retention and often include materials like expanded clay or pumice with up to 70% moisture retention.
- Filter layer fabric, positioned atop the drainage layer, acts as a separation medium between the substrate and the drainage layer. This aims to prevent and avoid the penetration of smaller particles from entering and clogging the drainage layer. Additionally, it aids in filtration as it traverses through the various layers, ensuring a well-maintained and effective drainage system. It has tiny pores that cause high water permeability, at least ten times higher than the substrate's. To ensure the choice of the filter layer, it must be characterized by specific criteria such as the ability to withstand the weight overhead and punching resistance (>1.100 kN), its tensile strength must be greater than 7.0 kN, its effective pore opening should oscillate between 0.10 and 0.20 mm, and its deformation to the longitudinal operating load and the transverse working load must be lower than 60%. Finally, it should be resistant to aggressive agents. This layer usually employs two common materials: granular material and non-woven geotextiles.

  - Granular materials, including pozzolana, pumice, lapilli, expanded clay, perlite, slate, and crushed bricks, exhibit water permeability exceeding 0.3 m/s.

    - Non-woven geotextiles, such as polymeric fibers or polyolefins, having a water permeability of more than 0.3 cm/sl × 10^{-3} m/s, can absorb 1.5 L/m^2 of water. These materials are used to manufacture thin and light filter layers regularly.
- The drainage layer beneath the filter layer makes water available to plants through capillary action to support evapotranspiration and plant health. The green roof has water retention ability; thus, keeping empty spaces between the layers is vital to facilitate the excess water flow out of the roof structure. Simultaneously, the drainage layer helps to remove excess water, decreasing the risk of water leaks, thus bypassing the oversaturation of the substrate and root zone and reducing waterlogging efficiently to provide a suitable equilibrium between water and air, ensuring adequate ventilation for the roots. This balance maintains optimal moisture for vegetation while preventing water accumulation that can damage plant roots or reduce the roof's thermal and insulating properties. Since water adds extra weight to the roof assembly, evacuating water professionally decreases the load on the structure and minimizes the risks of mechanical degradation and breakdown. Moreover, the drainage layer safeguards the waterproof membrane and improves the thermal performance of the green roof. By filling it with a minimum of 60% air, the correct conditioning of this layer preserves the vegetation and prevents its deterioration. It is usually suitable in moderate climates with 500–1000 mm of annual rainfall. Regarding humidity, it is designed to handle low to high precipitation rates: the typical drainage layer thickness is 2–5 cm, which is sufficient for regions ranging from 250 mm to 1200 mm of annual rainfall, thus ensuring rapid water removal to prevent excess retention. Again, the materials for this layer depend on the type of green roof, climate, and roof assembly. The two universal materials used are as follows.
    - Granular materials should have a minimum thickness and density of 6 cm and 150 kg/m^3, respectively. When porous, these materials can also serve as water storage. Some of the frequent granular materials are expanded clay pozzolana, pumice, expanded perlite, lapilli, expanded slate, and crushed bricks.
    - Modular panels weigh approximately 20 kg/m^2, and their thickness falls within 2.5 to 12 cm. Constructed from robust synthetic or plastic materials, such as polyethylene or polystyrene, these panels feature cavities designed for water storage while ensuring adequate drainage of excess water.
- The protection layer is above the waterproofing membrane and acts as a separation and protection layer. It is typically added for supplementary protection to the waterproofing and anti-root membrane. Due to its ability to endure loads and stresses during the construction, installation, maintenance, and operational phases, it is installed to shield the underlying layers and prevent damage to the waterproofing membrane. Generally, this layer's materials are geotextiles, polystyrene, or geogrids with a thickness of 3 mm or more and a compression resistance of at least 150 kPa. These materials can collect water that the vegetation will use during drought periods. Even though they are added for more support for the green roof, they do not replace the anti-root membrane.
- Waterproof and anti-root membrane: the primary role of the waterproof membrane is to shield the building from potential infiltration due to the elevated water content in the upper layers, making it a crucial element in green roof technology. Concurrently, the vegetative roof protects the waterproof membrane, mitigating the impact of temperature fluctuations and solar radiation factors that can lead to the deterioration of the membrane's performance. The waterproofing membrane's design closely resembles that of a conventional roof. Nevertheless, in contrast to a traditional roof, the waterproofing membrane in a green roof is shielded from UV rays, thermal variations, and hail. This membrane may be exposed to biological and chemical agents present in the substrate and vegetation. For the waterproof membrane, bituminous flexible membranes are the most common and can be broken down into three types:

elastomeric membranes, plastomeric membranes, and elasto-plastomeric membranes. These bituminous membranes can be laid and installed as a monolayer or double layer of three- or four-millimeter thickness. These membranes have different characteristics and behaviors. Still, the compound, the glass or polyester reinforcement, and the protective surface finish realize a typical stratigraphy. These membranes exhibit diverse characteristics and behaviors, yet they share a standard stratigraphy composed of the compound, glass or polyester reinforcement, and the protective surface finish. The role of the anti-root membrane is inevitable, as the aggressive capacity of the root system must not be underestimated. Its primary purpose is to protect the waterproof membrane and the roof's structural integrity against the intrusion of vegetative roots from the upper layers. The plant's roots must not be underestimated, as they have the potential to cause mechanical disturbances and chemical alterations to the waterproofing membrane. Consequently, incorporating an anti-root layer is imperative in green roof construction, with it being integrated into the waterproofing membrane in nearly all instances. This layer's main characteristics and materials resemble those of the waterproofing membrane. On the contrary, the anti-root membrane must have high resistance and be adapted to microorganisms contained in the soil, which is achieved by adding repellent ingredients to the chemical composition of the anti-root membrane. It usually has a thickness of around 4 mm and is positioned with hot-air welding or a chemical solvent. A general misconception is using concrete as an anti-root barrier. This is not possible, as over time, the roots will eventually attack the concrete layer, making it very difficult to maintain the waterproofing membrane. In general, the waterproofing membrane serves in hot, moderate, and extreme climate conditions, with temperatures ranging between 20 °C and 40 °C in summer and −20 °C and 15 °C in winter, depending on the material. In terms of humidity, these membranes serve well and are effective in moderate to high rainfall and humidity.

- In some green roof designs, an insulation layer is introduced to establish thermal resistance and enhance energy efficiency. The leading role of this layer is to regulate the temperature inside the building by decreasing heat loss in cold months and cutting heat gain during warm periods. It is introduced below the growing medium and vegetation layers. The typical insulation materials for a green roof system are extruded polystyrene (XPS), rigid foam boards, expanded polystyrene (EPS), and mineral wool. The location of the building, the climatic conditions, and building codes direct the choice of material and the thickness to be used. The insulation layer contributes to the building's overall sustainability and energy performance.

3.2. *Green Roof Types*

Usually, three types of green roofs co-exist simultaneously (Figure 3)—extensive, intensive, and semi-intensive—which are classified according to weight, substrate material, maintenance, plant type, and irrigation [39,51–53].

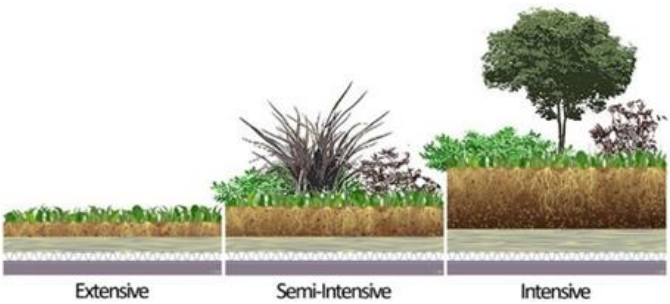

Figure 3. Types of green roofs [54].

3.2.1. Intensive Green Roofs

Intensive green roofs are generally roof gardens fabricated with a considerable substrate depth of more than 15–20 cm to accommodate various plants mimicking ground-level landscapes [55]. The depths of the media and the plant root are directly proportional. That implies that the plant roots dig more profoundly as the medium's depth increases, yielding a larger plant. Plants such as trees, shrubs, herbs, grasses, and flowers can grow freely and mature to many feet tall by maintaining the proper media on an intensive green roof [31,56]. Since this green roof can adapt to many plants, the labor needed to supervise and manage it is considerable. As the name implies, intensive green roofs require high maintenance through watering, weeding, and fertilizing. Due to the size and type of plants, the intensive green roof is heavy, ranging from 180–500 kg/m^2, and has a high water retention capacity exceeding 50% and a high capital cost reaching USD 25/ft^2. It possesses many advantages, most notably that it replicates a natural environment, provides a recreation space with enriched biodiversity, and serves as a getaway for humans for entertainment [29]. Due to their high water retention capacity, intensive green roofs have better potential in stormwater management than extensive green roofs, decreasing runoff by 85% compared to conventional roofs [57]. In terms of drawbacks, the primary one is that intensive green roofs require additional structural reinforcement due to their heaviness and irrigation/drainage must be integrated, thus increasing their technical complexity and expenditure [32].

3.2.2. Semi-Intensive Green Roofs

Semi-intensive or simple intensive green roofs (SIGRs) are intermediate between extensive and intensive green roofs. These can withstand small herbaceous plants, grasses, or even miniature shrubs, requiring only mild maintenance and occasional irrigation in temperate climates, such as Central Europe. Irrigation may come in handy when the environment faces prolonged periods without precipitation, and the amount required is calculated based on the demand of the plants. Unlike the intensive GR, the advised substrate thickness varies between 12 cm when planting grass or herbaceous plants and 20 cm for smaller shrubs and coppices. Of course, a more complex vegetation system requires an increased substrate thickness. One of its key advantages is that it provides high thermal resistance, which is now in demand in contemporary low-energy architecture. Its substrate layer thickness allows more stormwater retention and fosters a richer habitat, making it a more suitable replacement for built-up land than an extensive green roof [58].

3.2.3. Extensive Green Roofs

Forests, agricultural fields, and suburban and urban lands are being substituted by impervious surfaces due to ongoing development and growth. This necessitates working on recovering green spaces to ensure that they are maintained. One of the solutions is the extensive green roof system. It is a good platform for shallow-root-system plants with high drought-resistance capacity as it has a lower substrate depth (<15.2 cm). The plant species are limited to herbs, grasses, mosses, and drought-tolerant succulents such as sedum and are left to grow naturally as they care for themselves. They only require yearly weeding and fertilization. Extensive green roof systems are much cheaper, making them more suitable for many urban buildings, and generally require minimal maintenance. Unlike the former, these are not accessible to the public and may not even be visible. The primary benefits of extensive roofing systems include their economical initial investment, minimal maintenance needs, and lower water demands compared to intensive roofs [59]. These roofing structures are typically characterized by their lightweight nature, making them particularly advantageous when additional structural support is unnecessary. Moreover, extensive roofs can be implemented on steeper slopes, and their construction process is technically straightforward, rendering them suitable for large rooftops. Nevertheless, the energy efficiency and stormwater management capabilities of extensive green roofs are comparatively modest [60]. Among the two categories, extensive roofs are prevalent globally, primarily attributed to their lightweight nature, independence from irrigation, and lower initial and maintenance expenses [40]. Table 1 depicts a clear comparison between the well-known and utilized types of green roofs.

Table 1. Comparison between the three types of GR.

	Extensive Green Roofs	**Semi-Intensive Green Roofs**	**Intensive Green Roofs**
			
Maintenance	Low	Periodic	High
Irrigation	No	Periodic	Regular
Plant Species	Moss, Sedum, Herbs, Grasses	Shrubs, Herbs, Grass	Lawns, Shrubs, Trees
Height (mm)	60–200	120–250	150–400
Weight (kg/m²)	60–150	120–250	180–500
Costs	Low	Intermediate	High
Energy Saving	Reduces cooling energy use by 20–40% and heating energy use by 10–15%	Reduces cooling energy use by 30–50% and heating energy use by 15–25%	Reduces cooling energy use by 40–60% and heating energy use by 20–30%
Climatic Area	- Temperature: Moderate climates with temperature ranges between 5 °C to 25 °C - Humidity: Moderate to low humidity.	- Temperature: Temperate climates and some extreme conditions, with temperature ranges of −5 °C to 30 °C. - Humidity: Moderate to high humidity	- Temperature: Moderate to extreme temperatures from −15 °C to 40 °C - Humidity: Both high and low humidity

3.3. *Green Roof Energy Performance Benefits*

Apart from their visual appeal and environmental benefits, these roofs are pivotal in optimizing energy usage. This review delves into how green roofs can contribute to reduced heat transfer, lower energy consumption, and improved insulation for the installed structure, thus promoting a more sustainable and eco-friendly built environment. In addition, the direct impacts of green roofs on a building's energy efficiency are presented through various case studies. Moving on to the broader implications for urban environments, green roofs alleviate the urban heat island effect and contribute toward a more energy-efficient urban landscape. Understanding their energy performance benefits becomes paramount as the global community shifts to innovative approaches to promote sustainability and counteract climate change. There is consensus that integrating green roofs is a viable strategy for advancing energy-efficient building practices and fostering resilient, environmentally conscious urban spaces [61,62].

3.3.1. Building Energy-Saving Benefits

When dealing with green roofs and facades, the most significant forms of energy impacted are thermal, solar, and electrical energy. Green roofs and facades primarily affect the flow of heat, mainly thermal energy, between the building and the external environment. The addition of soil, plants, and other layers above the conventional roof structure serves as a thermal barrier, reducing heat loss during cold seasons and minimizing heat gain in hot seasons. This contributes to stabler indoor temperatures and reduces the need for energy-intensive heating and cooling systems. In terms of solar energy, these technologies play an essential role in managing solar radiation, which impacts the building's energy performance as the vegetation and soil of the green roofs absorb and reflect a portion of incoming solar energy, preventing it from heating the building. This solar energy is either used for photosynthesis for plants or is dissipated through natural cooling processes like evapotranspiration. By absorbing and reflecting solar energy, as depicted in Figure 4, green infrastructure reduces the amount of heat transferred into the building, lowering cooling loads in summer. One of the most important benefits of green roofs and facades is the evaporative cooling phenomenon that mainly targets latent heat energy and contributes to cooling through evapotranspiration. Through this, heat from the surroundings is absorbed, thus lowering surface and ambient temperatures. The cooling effect reduces the need for air conditioning and enhances the overall energy efficiency of the building by moderating temperature fluctuations. The layers and materials used in green roofs and facades, like soil and vegetation, can store energy in the form of heat, moderating temperature changes throughout the day. By optimizing and understanding the optimum environments and conditions for each of these technologies, green infrastructure significantly contributes to lowering energy consumption, improving insulation, and creating more sustainable, energy-efficient buildings. Therefore, the influence of the building envelope on energy consumption is undeniable. Statistics show that the energy dissipated in the building industry is reaching one-third of the energy consumption for heating and cooling employed to maintain the internal building temperature. Also, due to global warming, energy consumption is following an exponential trend, approaching 50% in cold climates [63]. In buildings, heat loss occurs typically through walls, roofs, and floors due to the external areas of the building. Thus, by providing the correct manner of insulation against this heat loss during cold or hot weather, this energy consumption can be remarkably decreased [11]. Based on much research conducted in recent years, the building sector is indeed one of the most energy-intensive industries, constituting approximately one-third of the global primary energy demand and representing a substantial contributor to energy-related greenhouse gas (GHG) emissions [64]. In one of their reports in 2017, the United Nations stated that building construction and operations contributed to 36% of the total global energy consumption and around 39% of energy-related carbon dioxide (CO_2) emissions [65]. The final energy consumption calculations in buildings showed an increase from 118 EJ in 2010 to approximately 128 EJ in 2019, a 5% increase. Consequently, direct emissions from buildings surpassed 3 Gt carbon oxide in 2019, representing a 5% rise since 2010. If these trends persist, the building industry is anticipated to become the world's foremost energy consumer by 2025, surpassing the combined energy consumption of the transportation and manufacturing sectors [66]. In addition to green roofs, the cool–green roof has recently gained attention. This is an innovative roof that combines features from both green and cool roofs. It was shown that this roof also has thermal benefits, as it reflected 44% of the incident solar radiation, which is 6% more than a standard concrete roof and 7% more than a traditional green grass roof, with negligible negative effects in winter [39].

Throughout the literature, various detailed and diverse studies have exploited green roofs as an attractive option for energy saving in a building due to their thermal impact and properties [48,67]. Through the shading and protection from solar radiation that they offer, buildings' energy consumption is reduced, especially during summer. Due to the presence of the plantations, evapotranspiration is a dominating phenomenon that will contribute to humidifying and cooling the surrounding air, greatly decreasing the urban heat island effect [68,69]. In their research, Liu et al. found that with the incorporation of a green roof on a building, the thermal insulation is automatically improved, reducing the solar heat gain by around 70–90% in the summer and the heat loss by nearly 10–30% in the winter period. Niachou et al. [70] investigated the advantages of incorporating a green roof in enhancing the energy efficiency of a building. Their research specifically addressed the integration of green roofs into buildings with different levels of existing insulation in Athens. Two buildings with similar insulation properties were examined, one featuring a green roof and the other without. The study monitored the internal temperatures of both buildings over a three-day testing period. The findings revealed that with the green roof, the internal air temperature exceeded 30 °C for only 15% of the testing period, whereas without the green roof, this percentage increased to 68%. They also showed that the green roof area and the cooling energy were proportional, as the energy needed for cooling fluctuated between 2% and 48% depending on the area traversed by the green roof, and the inner indoor temperature was reduced by up to 4 °K. In Toronto, Canada, Martens et al. [71] concluded that installing 250×250 m green roofs with a 50,000 W internal loading on the building reduced the overall energy consumption by 73%, 29%, and 18% for the top and first and second floors below it, respectively. According to the findings of Dimitris et al. [72], 27% of the incoming solar radiation on a green roof was reflected, the plants and the substrate medium absorbed 60%, and 13% was transmitted through the substrate medium. Several studies in the literature concluded that the thickness of a green roof's substrate can remarkably affect the roof's thermal insulation capacity. Permpituck and Namprakai et al. [73] tested the insulation of three roofs: two were green roofs with substrate thicknesses of 10 and 20 cm, and the third was a regular roof. A remarkable reduction was noticed in the heat transfer and energy consumption of the building: heat transfer decreased by 59% and 96% and energy consumption by 31% and 37% for the 10 and 20 cm-thick green roofs, respectively, in comparison to the conventional bare roof. In a similar study, Liu and Minor et al. [74] also tested the effect of substrate thickness. They assessed the heat-transfer rate through two green roofs, one 75 mm and one 100 mm thick, with respect to a bare roof, and it was validated that the thermal performance of green roofs depends on the depth of the greenery surface. Also in this regard, Wong et al. [75] conducted field measurements to highlight the benefits of green roofs for insulation and energy-saving purposes. Their study showed that the heat gained throughout the day in a conventional roof was constantly transmitted to the inside of the building at night, unlike the green roof that faced less heat gain during the day. In addition to that, they calculated the air temperature at various heights above the green roof, showing that, especially after sunset, the temperature of the ambient air above the vegetation layer diminished remarkably. It was also concluded that the green roof impacted the insulation properties by creating a balance between the losses in winter and gains in summer, with an energy-saving possibility between 0.6% and 14.5% for a five-story commercial building in Singapore. In Canada, MacIvor et al. [76] replicated an extensive green roof modular array. They installed five sensors in its structure to monitor the temperature change along a vertical gradient, thus examining the effects of irrigation and attributes of the vegetation and substrate. It was shown that in two seasons, there was a 2 °C difference at the surface of the substrate and a 1.5 °C difference 15 cm above the substrate layer. Based on their experiments, the vegetation type and cover were found to be essential criteria for roof cooling, where a sedum crop had significant cooling effects on the roof compared to meadow vegetation. A study on European climates conducted by Ascione et al. [77] illustrated that even in warm climates, green roofs offer a viable solution for diminishing the energy requirements associated with space cooling while minimally affecting the already limited demand for heating. Studies indicate an annual decrease in primary energy demand ranging from 1% to 11% for Tenerife, 0 to 11% for Sevilla, and 2% to 8% for Rome. Moreover, in colder climates, green roofs serve to mitigate energy needs for both cooling and heating, resulting in annual savings of approximately 4% to 7% for Amsterdam and London and 1% to 6% for Oslo.

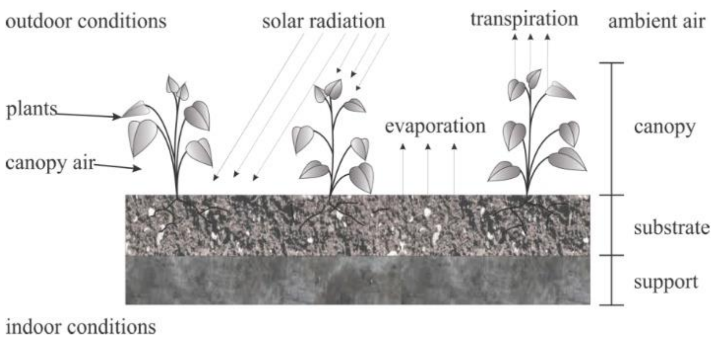

Figure 4. Schematic cross-section of a green roof [78].

3.3.2. Green Roof Modeling and Experimental Testing

The concept of green roof integration on buildings is burgeoning and is gaining momentum globally. In turn, the evaluation of their performance is now growing. Hence, considerable research has established effective and reliable tools for design modeling and assessment, allowing researchers to understand dynamics and optimize design. Modeling of green roofs, or in other words, the development of computational frameworks to simulate their behavior under numerous conditions, focuses on areas such as insulation layer, substrate composition and thickness, plant physiology and types, environmental variables, long- and shortwave radiative exchange within the vegetation layer, and evapotranspiration from plants and soil [79] to predict outcomes like temperature regulation and thermal impact, reduction in heat flux and solar reflectivity, water retention, energy savings, and biodiversity and ecological impact. Refining these models is crucial for understanding the methods that contribute to improving the effectiveness of green roof installations and evaluating their performance in real-world scenarios. This review targets a thorough overview of the existing literature on green roof modeling and assessment methods to form a dataset for the current state of research in this field. This critical analysis aids in identifying the gaps in the field, highlighting the emerging trends, and proposing avenues for future investigations [80]. Within the existing body of literature, a plethora of models outlining the dynamics of green roofs persists, exhibiting a spectrum of complexity spanning from rudimentary to intricate [28]. The basic models consider only the U-value decrease in the roof. The others, on the contrary, calculate the heat balance, taking into account additional phenomena such as the solar shading effect and evapotranspiration [71,80–84]. Digging deeper, through her thermal mathematical model, Del Barrio [81] studied the influence of green roofs on the energy performance of a building. In her model, the green roof was split into three parts—the canopy, soil, and roof slab—in which she assessed heat balance at each of the canopy–soil, soil–roof slab, and roof slab–indoor air interfaces. The FASST (fast all-season soil strength) model in the study of Frankenstein and Koenig et al. [82] computed heat balances on a roof soil surface and a foliage surface. It was found that the heat transfer in the green roof was primarily influenced by factors such as foliage height, leaf area index (LAI), fractional vegetation, coverage, albedo, and stomatal resistance. The heat and mass transfers were assessed based on the assumption that the leaf was a solid body on which air circulates. In light of their work, in his article, Sailor [80] also evaluated the energy balance designed for green roofs in which his model was linearized, integrated into the EnergyPlus program, and validated on a University building in Florida. Later, it was employed to estimate the energy consumption for office buildings in Chicago and Houston.

Ouldboukhitine et al. [85] depicted a coupled heat- and mass-transfer model, which is based on the Penman-Monteith equation that takes into account the effects of water transfer on the thermal properties of the substrate. In their works, Getter et al. [86] attempted to compose a model for monitoring the thermal behavior of vegetated green roofs based on field testing and the theory of building physics. In their models, different parameters were used to highlight the physical processes in and around the vegetated green-roof construction. In Greece, Niachou et al. [70] worked on a mathematical model to calculate heat transfer for the cooling seasons. Based on the results they obtained, it was shown that the addition of air pockets in a thin substrate enhanced the thermal performance of a green roof. Also, decreasing the soil moisture causes a decrease in the heat flux through the roof. The thermal resistance of soil increased by 0.4 m^2 K/W when using a 100 mm-thick growing medium. Following Del Barrio, Kumar and Kaushik [83] also devised a mathematical model designed to assess the thermal effects of solar shading and green roofs. The model underwent validation using empirical data obtained from a green roof in Yamuna Nagar, India. The results demonstrated that manipulating the leaf area index (LAI) significantly influenced the canopy air temperature, reducing the stabilization of its fluctuation and diminishing heat flux through the roof. Alexandri and Jones [87] made a noteworthy contribution by formulating a two-dimensional model to investigate the influence of green roofs and walls on the microclimate within a standard urban canyon. Their study spread the analysis across nine diverse climates. Concerning the outcomes of the roof surface, it was shown that the most significant reduction in both mean temperature and maximum temperature occurred in Saudi Arabia, specifically Riyadh, with a decrease of 12.8 °C, and in Mumbai, with a decrease of 26.1 °C. Feng et al. [88] conducted an exhaustive examination of the overall heat balance throughout a roof, wherein they postulated the dominance of photosynthesis and presupposed a known leaf temperature within the system. The work of Tabares-Velasces et al. [89] provided a quasi-steady-state heat- and mass-transfer model that can be merged with diverse energy simulation software or calculation procedures. In this model, the heat- and mass-transfer processes are those between the sky, plants, and substrate. Their work introduced novel equations for the computation of the thermal conductivity and resistance of substrates in green roofs to estimate the soil evaporation rates in green roofs and compute the transpiration in plants through a series of stomatal resistance functions. Another dynamic model for the calculation of transient heat and mass transfer across a green roof installation is the study of Djedjig et al. [90,91], in which the thermal behavior of the green roof layers is modeled and coupled to the water balance in the substrate layer. Its variations account for evapotranspiration intensity impacts and the substrate's physical properties. Their demonstrated thermal and hydric model integrates the impact of wind speed within the foliage by employing a novel calculation for the resistance to heat and mass transfer within the leaf canopy. The developed model was validated using experimental data obtained from a one-tenth-scale green roof situated at the University of La Rochelle. Surface temperature variations to 25 °C are observed between green roofs employing a dry growing medium and those utilizing a saturated growing medium. The green roof installed at Vicenza Hospital in Italy helped in the development of a predictive model in the study of Lazzarin et al. [92]. Based on the building simulation software TRNSYS, the thermal and energy performances of the structure with a green roof were calculated by varying the meteorological dataset for a specific geographic zone. The experimental sessions used data loggers installed in the layers of the green roof with humidity, temperature, radiation, and rainfall sensors that displayed the data related to the green roof itself and the room beneath it. Moody and Sailor [93] developed and applied a building energy performance metric for green roof systems. In their article, the validation of the dynamic benefit of green roofs (DBGRs) performance metric was executed through EnergyPlus, utilizing empirical data and accounting for four ASHRAE climatic regions. The overall annual performance of green roofs surpassed that of conventional roofs. A comprehensive study utilizing EnergyPlus conducted by Yaghoobian et al. [94] encompassed 30 building cases that varied in terms of leaf area index (LAI), building type, and building age in Baltimore, Phoenix, Maryland, and Arizona. The study findings indicated that the substrate surface temperature of green roofs exhibited a decline as plant coverage increased. This phenomenon was primarily attributed to a reduction in absorbed solar radiation on the substrate surface and an increase in evaporation. Zhang et al. [95] investigated the characteristics of green roofs on pedestrian cooling in neighborhoods. They based their studies on the ENVI-met model to assess the impact of various factors, including the arrangement of greenery, vegetation coverage ratio and height, and building height, on the reduction in pedestrian air temperature in the tropical urban setting of Hangzhou, China, After a simulation of 30 h, the findings revealed that green roofs exhibited a capacity to reduce the temperature by between 0.10–0.30 °C, while demonstrating an overall cooling efficacy of 0.82 °C. The location of the green roofs also had a remarkable role in which green roofs situated in upwind areas exhibited the most significant cooling effects, whereas those in downwind regions showed marginal improvements in pedestrian thermal comfort. Additionally, the analysis indicated that green roofs with lower vegetation coverage ratios were less effective in mitigating pedestrian temperature. In contrast, a greening coverage ratio ranging between 25% and 75% in upwind zones emerged as a cost-effective solution for enhancing thermal comfort within real urban neighborhoods.

Aiming to optimize green roof design and operation in buildings, Mousavi et al. [96] proposed and studied a novel energy–comfort system designed for green roofs in housing that was coupled with machine learning (ML), DesignBuilder (DB) software V.60.1.19, and Taguchi design computation. The ML analysis was conducted on MATLAB, the DB software that modeled the design of the green roof, and through it, the optimal design for a green roof was assessed using sensitivity analysis and regression output. The energy conservation and thermal comfort within green roof buildings were enhanced by optimizing key parameters, including leaf area index, leaf reflectivity and emissivity, and stomatal resistance. This process generated optimal solutions, leading to a noteworthy increase of 12.8% in comfort hours and a significant reduction of 14% in energy consumption compared to the baseline scenario. The Sugeno FL method was used to extract the effective parameters, which were then fed into an adaptive neuro-fuzzy inference system (ANFIS). It was determined that the ANFIS was the most suitable method for predicting energy–comfort functions based on the effective parameters, with a correlation coefficient exceeding 97%. Hong et al. [97] derived an energy model in which the calculation of the effects of radiation, convection, and evaporation effects on the surface temperature was simplified to depend on fewer unknown variables. Hence, what is interesting about that model is that it solely needs primary meteorological data and an initial soil temperature measurement to predict the green roof surface temperature within any equation-solving framework. In their article, the formulations governing the heat transfer in green roofs were simulated using MATLAB numerical computation software. The coefficients incorporated within these models were derived from a combination of empirical experiments, estimations, and established measurements. The simulated soil temperature derived from the MATLAB model was compared to the measured experimental one to validate the energy balance model. Capozzoli et al. [79] defined a simplified thermal parameter that was assessed through a dynamic energy simulation that facilitated the characterization of the thermal behavior of a green roof during the summer period. A sensitivity analysis was performed to estimate the most important design variables affecting the proposed parameter, and the conductive heat flux through the inner surface was calculated. In Mexico City, the thermal performance of two buildings, one conventional and the other with an integrated green roof, was studied as part of the work of Polo-Labarrios et al. [98]. They developed a transient mathematical model that took into account the heat transfer through the roof and walls and computed the energy balance to calculate the change in the temperature inside the building. The differential equations were numerically solved by the finite difference method, and the model results verified that the green roof reduced the temperature fluctuations inside the building to 14 °K compared to traditional ones. Additionally, the green roof contributed to the achievement of a comfortable temperature, where the inner building temperature was reduced by up to 12 °K, even in the warm climate of Mexico City. Ayata et al.'s [99] study utilized genetic algorithm software to derive and obtain equations. It proposed a basic model comprising the modified Newton's cooling law, the logarithmic wind profile model, and McAdams' model for calculations to assess the free and forced convective heat transfer and sensible heat fluxes on green roof assemblies by varying environmental conditions in a laboratory setup. A new computer model to solve green roof-associated differential equations known as the continuous system modeling program (CSMP) was applied by Takakura et al. [100]. Using this simulation language, they were able to simulate systems and evaluate a green roof's cooling load. In Athens, Santamouris et al. [101] analyzed a building's energy conservation using a mathematical model coupled with the dynamic simulation program TRNSYS 15.1, which computed both the cooling and heating demands throughout the summer and winter seasons for both the entire building and its uppermost floor. The energy performance assessment revealed a notable decrease in the building's cooling requirements during the summer months. This reduction varied, encompassing a range of 6–49% for the entire building and 12–87% for its top floor. Furthermore, the impact of the green roof system on the building's heating demands was deemed insignificant, presenting a significant advantage of the system. Typically, any addition to the building envelope aimed at reducing cooling demands tends to result in an increase in heating demands, making the lack of influence on heating demands particularly advantageous. In Table 2 below, the numerous simulations and major findings relating to the energy benefits of green roofs are presented, with many subtopics related to each presented study.

Although significant progress has been made in the development and implementation of green roof technologies, there remains substantial potential for further innovation and improvement. Emerging advancements in materials, water management strategies, and design optimization continue to offer new opportunities to enhance the efficiency, performance, and sustainability of these green systems. To start with substrate choice, innovative light and high-performance substrates incorporating materials like biochar or recycled glass aggregates offer reduced bulk density and improved thermal insulation, which contribute to energy savings by keeping roof temperatures lower during hot periods, enhancing water retention while reducing the structural load on buildings. Moreover, advancements in water retention technologies, such as the use of capillary irrigation systems or water-retaining fabrics and multi-layer drainage mats, have improved the efficiency of water use, allowing green roofs to retain moisture for longer periods, reducing the need for supplemental irrigation and preventing waterlogging, which is particularly beneficial for regions with variable rainfall. Finally, modular green roof systems have emerged that feature pre-planted units, removable trays, or modules that are assembled and placed directly on the roof surface. These modular units are pre-grown in nurseries, and hence the plants are already well established before installation. These trays contain all the necessary layers, including the growing medium, drainage, and water retention elements, permitting quick and easy installation. This system is very flexible, as the individual trays can be replaced or removed without disturbing the rest of the roof, making maintenance more straightforward and less expensive [11,16,24,27]. However, despite these advancements, a critical evaluation of the long-term costs, maintenance, and sustainability of various green roof systems is essential. As mentioned before in Table 1, extensive green roofs are the most economical due to their shallow substrates that range between 6 and 20 cm, minimal maintenance, and generally low cost, with installation costs ranging from USD 100–150 per square meter. Nevertheless, they offer limited stormwater retention capacity, as they only retain 50–70% of annual rainfall, reducing biodiversity. On the flip side of the coin, semi-intensive and intensive green roofs with deeper substrates of 20–50 cm or more provide greater environmental benefits, such as enhanced biodiversity and stormwater management, as the retention reaches up to 100% of the rainfall, but come at a higher cost, often exceeding USD 150–400 per square meter. Based on their features, these systems demand more maintenance, such as regular irrigation, plant care, and structural checks, which add to long-term operational costs. From a sustainability perspective, the integration of sustainable materials, such as recycled plastic drainage layers and organic substrates, helps mitigate the environmental footprint of green roof systems. However, long-term sustainability depends on achieving substantial energy savings and reducing carbon emissions over time. Green roofs are most sustainable in urban settings, where they contribute to cooling the urban heat island effect and reduce building energy demands by up to 30% during the summer months. Although advancements in technology have enhanced the functionality of green roofs, choosing the right system involves carefully balancing upfront costs, structural load capacities, ongoing maintenance requirements, and long-term environmental benefits to optimize both performance and sustainability [55,57,96].

Table 2. Main green roof simulations and findings.

Authors/Publication Year	Model/Software	Location	Climate/Period of Study	Advantages/Limitations	Building Energy Performance	Ref.
Niachou et al., 2001	Mathematical model	Greece	Summer	Advantages: Evaluation of the GR thermal properties through experimental and mathematical measurements. Calculation of the GR total energy-saving consumption of buildings. Analysis in both indoor and outdoor environments to assess microclimate effects. Uses computational codes and numerical simulation models to study thermal performance. Limitations: Specific location and building type, potentially limiting generalizability. A specific set of scenarios for night ventilation which may not fully represent real-world conditions.	In scenarios without night ventilation, heating energy savings in buildings with non-insulated roofs ranged from 9% to 45%. Cooling loads showed no savings in well-insulated buildings but up to 45% in non-insulated ones, with total yearly savings between 2% and 44% depending on insulation and scenarios. Introducing night ventilation significantly increased summer energy savings, hitting 54% to 61% in non-insulated and 9% to 12% in moderately insulated buildings.	[70]
Capozzoli et al., 2013	Mathematical approach	Torino, Italy	Summer	Advantages: Simplified methodology for GR configuration energy evaluation. Defining GR dynamic thermal inertia as a simplified thermal parameter. Evaluating design variables through a sensitivity analysis. Implementing the FASST model in EnergyPlus for numerical analysis. Limitations: Lack of information on GR soil compositions and characteristics, as well as vegetation characteristics that influence the energy behavior of GR.	-	[79]

				Focus on the thermal behavior during the summer period, potentially neglecting seasonal variations. The impact of moisture levels in soils on energy performance has not been thoroughly evaluated.		
Sailor 2008	EnergyPlus building energy simulation	Florida	Local weather conditions	<u>Advantages:</u> Method for assessing the energy performance of GRs and assisting in the design process. Accounts for the effects of the drainage layer. The model was validated using data from a detailed field study in Florida, and prior versions of EnergyPlus were consistently reproduced. <u>Limitations:</u> The study is limited to the savings from air-conditioning in summer, and more comprehensive design tools that consider other factors and seasons are needed. The study enabled only a single GR construction, limiting its applicability to buildings with multiple roof constructions. The model does not clearly model sensitivity to parameters like soil thickness, vegetative cover, and irrigation.	-	[80]
Del Barrio 1998	Mathematical model	Athens	Summer	<u>Advantages:</u> The model provides a simplified representation of the dynamic thermal behavior of real GRs. It allows for the analysis of the cooling potential of GRs in summertime. <u>Limitations:</u> The model assumes a homogeneous layer for the canopy, which may oversimplify the actual spatial complexity and heterogeneity of foliage. It may not fully capture the turbulent nature of airstreams within and above a canopy, leading to potential inaccuracies in predicting energy and mass fluxes.	-	[81]
Frankenstein et al.,	FASST (fast all-season soil	-	Winter—cold snowy weather	<u>Advantages</u>	-	[82]

2004	strength) model/1D dynamic state-of-the-ground model			Comprehensive one-dimensional dynamic state-of-the-ground model FASST. Accounts for various factors affecting energy and moisture in vegetation canopies. Accounts for canopy energy dynamics, longwave and shortwave fluxes, interactions between different canopy layers, and sensible canopy heat and evapotranspiration flux calculations. <u>Limitations:</u> Accounts for surface conditions measurements only. Specific vegetation type (broadleaf deciduous) and mean canopy density.		
Kumar and Kaushik 2005	Fast Fourier transform (FFT) techniques in MATLAB + Newton's iterative algorithm.	Yamuna Nagar, India	Summer (May–June)	<u>Advantages:</u> Comprehensive set of experimental data was used for verification of the model. Incorporation of parametric variations in thermal components of GRs. Coupling the GR model with the building simulation code for a more holistic analysis. Validation of simulated results with experimental data showing good accuracy. <u>Limitations:</u> Restricted applicability of the GR model to specific buildings due to localized experimental data. Need for the specification of specific parameter values according to building specifications.	An increased LAI, a peak reduction of 9.3 °C in canopy air temperature, was observed over a cycle of 8 days: June 1–8. The peak canopy air temperature and temperature width were both reduced as LAI increased, leading to a significant reduction in fluctuations from 11.6 °C to 3.6 °C with an increase in LAI from 0.5 to 3.5. A combination of the GR and solar thermal shading reduced the indoor air temperature by an average of 5.1 °C compared to a bare roof. The GR alone provided a cooling potential of 3.02 kWh per day, which is adequate to maintain a room air temperature of 25.7 °C. Integration of the GR showed energy savings in terms of reduced indoor air temperature by an average of 7.2 °C.	[83]
Ouldboukhitine et al., 2011	Heat- and Mass-Transfer Model	La Rochelle, France	Summer–winter	<u>Advantages:</u>	-	[85]

				A detailed thermodynamic model that incorporates energy balance equations for foliage and soil media, allowing for a thorough analysis of GRs' thermal behavior. The model was validated using experimental data collected from a dedicated platform at the University of La Rochelle, enhancing its reliability. Parametric analyses evaluate the influence of various parameters on the model output, providing insights into how different conditions affect the performance of GRs. Limitations: Validated based on specific weather data from La Rochelle, France.		
Alexandri and Jones 2008	Two-Dimensional, Prognostic (Dynamic) Micro-Scale on C++ Software	London, UK	July—Temperate	Advantages: Use of a two-dimensional, prognostic micro-scale model allows for a detailed quantitative assessment of heat and mass transfer in urban canyons. Examination of various urban geometries and climates. Targets the heat island effect, a significant urban issue, and demonstrates how green infrastructure can mitigate this problem. Incorporation of various factors such as wind direction, solar radiation, and the hydrothermal properties of materials. Limitations: Based on typical days in the hottest months, which may not capture the full range of temperature variations throughout the year or during extreme weather events.	Energy savings range from 35% to 90%, depending on the specific conditions of the urban environment. In Riyadh, maximum temperature reductions can reach up to 11.3 °C, while the daytime average can decrease by 9.1 °C for the green-all case. A 90% decrease in cooling load with a reduction from 12 h to 5 h of cooling demand. In London and Moscow, reductions ranged from 1.7 °C to 2.1 °C. In Montreal, the cooling load decreased by 85%. In Mumbai, the cooling load decreased by 72%.	[87]
		Montreal, Canada	July—Subarctic			
		Moscow, Russia	July—Continental Cool Summer			
		Athens, Greece	July—Mediterranean Climate			
		Beijing, China	June—Semi-Arid or Continental Climate			
		Riyadh, Saudi	July—Desert			
		Hong Kong, China	July—Humid Subtropical			
		Mumbai, India	May—Rainforest			
		Brasília, Brazil	September—Savanna			
Feng et al., 2010	Energy Balance Model	Guangzhou, China	July—Summer	Advantages: Energy balance of extensive GR.	On a summer day, the soil was rich in water content; solar radiation accounted for 99.1%	[88]

				Development of an energy balance model that requires only eight parameters to understand and predict energy flows and balance Validation through field experiments conducted on a sedum linear GR. <u>Limitations:</u> The model does not consider conditions with precipitation, temperature drops, or humidity as a result of the dew.	of the total heat gain of a sedum linear GR, while convection made up 0.9%. Regarding dissipated heat, 58.4% was lost through evapotranspiration of the plant–soil system, 30.9% by the net longwave radiative exchange between the canopy and the atmosphere, and 9.5% by the net photosynthesis of plants. Only 1.2% of the heat was stored by plants and soil or transferred into the room beneath.	
Tabares-Velasco et al., 2012	Quasi-Steady-State Heat- and Mass-Transfer Model	-	-	<u>Advantages:</u> Validated through experimental data collected under controlled conditions. A heat- and mass-transfer model for GRs that can assess their thermal performance. <u>Limitations:</u> The validation process highlighted that differences in variables were outside experimental uncertainty for most variables, except for surface temperatures. The study initially considered a GR without plants, representing a worst-case scenario that may not reflect typical conditions of established GRs.	-	[89]
Djedjig et al., 2012–2013	Finite Difference Methods+ TRNSYS	La Rochelle, France	Oceanic Climate	<u>Advantages:</u> High accuracy, as the model demonstrated a mean temperature prediction error of only 0.8 °C, with 80% of computed temperatures closely aligning with experimental measurements, showcasing its reliability over 19 days. Incorporation of water availability in the soil, thus leading to an effective evapotranspiration calculation. Consideration of the thermal inertia of various components of the GR.	GRs offer significant energy savings through improved thermal insulation and reduced solar heat gain, reducing it by 70–90% during summer months and decreasing heat loss by about 10–30% in winter. A surface temperature difference of up to 25 °C was recorded between GRs with varying moisture levels. A saturation ratio of 50% maintains surface temperatures below 35 °C.	[90,91]
		Athens	Mediterranean Climate			

				Analysis of heat- and mass-transfer mechanisms on both foliage and soil surfaces. Parametric studies analyze how variables like water content and structural inertia affect surface temperatures. Validated against data from a one-tenth-scale experimental model. <u>Limitations</u> Dependent on accurate measurements of water content in the substrate. The experimental validation was conducted on a small scale (one-tenth). Validated based on specific weather data from La Rochelle, France.	A reduction in annual energy consumption due to GRs can range from 0.6% to 14.5%, particularly impacting the top floors of buildings.	
Lazzarin et al., 2005	TRNSYS Simulation	Italy	Summer August and September of 2002 and June and July of 2003. Winter February to March 2004	<u>Advantages:</u> Experimental measurements and numerical modeling of a GR highlighting its energy-saving and pollution-reducing potential. Evaluates the passive cooling effect and enhanced insulating properties of GRs during both summer and winter seasons. <u>Limitations:</u> Highlights the limited resources of experimental work and accurate analytical models in existing research that explain the evapotranspiration phenomenon. Evaluates the potential of GRs in reducing cooling and heating loads, but lacks extensive data on long-term performance and reliability in different geographic zones.	During summer, the thermal load of the rooms underneath decreased by about 60% compared to a traditional roof with an insulating layer. The GR's evapotranspiration process played a crucial role in passive cooling. It allowed for a slight outgoing thermal flux during winter, resulting in a 40% higher outgoing flux compared to high solar-absorbing and insulated roofing. During winter, the thermal gain entering the rooms underneath was reduced by 60%, showcasing its enhanced insulating properties in comparison to traditional roofing with an insulating layer.	[92]
Moody and Sailor 2001	EnergyPlus Simulation	Portland, Oregon Chicago, Illinois	Winter Spring Summer	<u>Advantages:</u> The introduction of the dynamic performance metric (DBGR) is a new metric that evaluates GRs' performance by comparing HVAC energy use with that of green and	In Portland's winter, the DBGR was 1.02, indicating a slight improvement (2%) in energy performance due to the GR's thermal storage effect, which moderated the	[93]

		Atlanta, Georgia Houston, Texas		conventional roofs. This metric accounts for the dynamic, time-varying nature of GR energy performance, making it more applicable to real-world scenarios. Multi-climate evaluation in four various climates (Atlanta, Chicago, Portland, Houston) offers insights into how GRs perform in different environmental conditions. Comprehensive energy simulation using the EnergyPlus simulation, the model incorporates various factors affecting GR performance, such as thermal storage, evapotranspiration, and radiative shielding. Validation using field data from a GR test facility in Portland, Oregon, enhancing its reliability and accuracy when applied to real-world buildings. <u>Limitations:</u> The model does not consider conditions with precipitation, temperature drops, or humidity as a result of the dew. Fixed soil moisture due to limitations in the EnergyPlus software. GR design specificity includes the thickness of the soil layer, the type of vegetation, and soil moisture content. Climate-specific limitations: The model showed a net energy consumption penalty in cooler locations, indicating that GRs may not always be beneficial in certain climates due to increased heating demands during shoulder season.	temperature swings. The DBGR value was 0.95 for spring and 0.92 for fall, indicating a performance penalty due to increased evaporative cooling, which leads to higher heating loads during these seasons. Annually, it was 0.97, meaning the GR performed 3% worse than a conventional roof due to undesirable evaporative cooling in the cooler seasons. The DBGR in Chicago in winter was 0.99, indicating that the GR slightly underperformed compared to a conventional roof. Meanwhile, the annual DBGR for Chicago was 1.01, showing that the GR performed 1% better than a traditional roof, with better performance in cooling-dominated seasons. The DBGR in Atlanta was consistent, with a value of 1.02 in winter and 1.03 in spring, summer, and fall. The annual DBGR was 1.03, meaning the GR provided a 3% improvement in energy performance. In Texas, the GR performed better than the conventional roof in all seasons, with DBGR values of 1.02 in winter and up to 1.03 in spring and summer. The DBGR for Houston was 1.03, showing a 3% improvement in energy performance over a conventional roof, driven by the GR's evaporative cooling effect.	
Yaghoobian et al., 2015	EnergyPlus Simulation	Baltimore and Maryland	Mixed–Humid Climate	<u>Advantages:</u> Comparison of the thermal effects of artificial turf (AT) with other materials like grass, asphalt, and concrete.	Using AT decreases overall building design cooling loads by 15–20% and has embodied	[94]

		Phoenix and Arizona	Hot- to Mixed-Dry Climate	Accounts for latent heat fluxes using the temperatures of urban facets in 3D (TUF3D) model. Limitations: Based on a specific geographical location and season, its generalizability is limited. Excludes long-term effects of AT on the urban environment, such as maintenance costs, durability, and potential environmental impacts beyond the immediate thermal effects.	energy savings of 10 Wh/m²/day due to irrigation water conservation. Grass ground cover was found to add 2.3 kWh/m²/day of heat to the atmosphere, potentially leading to urban air temperature increases of up to 4 °C. Overall, building design cooling loads near AT decreased by 15–20% compared to buildings near irrigated grass.	
Zhang et al., 2019	ENVI-met model simulation	Hangzhou, China	Tropical Urban Climate	Advantages: Simulations with variations in greening layout, coverage ratio, vegetation height, and building height. Analysis of cooling performances focusing on the pedestrian thermal environment at different times of the day. Comparison of cooling performance of GRs with and without greenery, providing valuable insights into the impact of GRs on thermal environments. Limitations: Limited timescale for the ENVI-met model. Constant wind speed and direction throughout the day in the model. The absence of the substrate layer of the GR in the model neglects the thermal effects of the soil.	GRs demonstrated moderate cooling effects on the environment at the pedestrian level compared to other cooling strategies, such as cool pavements, water bodies, and urban forests. The most favorable cooling performance of GRs was observed to be 0.82 °C Cooling performances for the GR ranged from 0.10 to 0.30 °C at various points.	[95]
Mousavi et al., 2023	Machine learning (ML), DesignBuilder (DB) software, and Taguchi design computation	Monterrey, Mexico	Semi-arid climate	Advantages: Optimization of the cooling and heating energy loads by analyzing effective parameters, leading to improved energy efficiency. Utilization of the Taguchi design principles and Minitab Employs energy modeling to assess the impact of different vegetation types on GRs, providing insights into energy use and occupant comfort conditions. Integration of machine learning with the DesignBuilder simulation enables the estimation of energy.	Reductions in the cooling load, with a value of 37.7 kWh/m². Reductions in the heating load, with a value of 93.8 kWh/m². GR can achieve a reduction of 6.2% in heating loads, showcasing the energy-saving potential of GR applications. Leaf area index (LAI), leaf reflectivity, emissivity, and stomatal resistance result in an annual energy savings of 114 kWh/m².	[96]

				Limitations: Complexity in data interpretation upon the use of advanced modeling techniques like ANFIS.		
Hong et al., 2021	Mathematical—Energy Models on MATLAB	Milwaukee, United States	Summer—August	Advantages: Simplified energy balance model for GRs that can be easily implemented in various software platforms like MATLAB, TRNSYS, or Grasshopper. Enables GR simulation without integrating it into the entire building performance, making it more efficient. Identifies critical factors that affect GR performance, such as surface color, soil depth, and plant type. Validated with real-world data from the University of Wisconsin—Milwaukee's Golda Meir Library. Explores the thermal dynamics of bare soil and vegetation-covered surfaces to demonstrate how factors like solar absorption, sky radiation, and plant characteristics influence surface temperatures. Limitations: Exclusion of weather conditions beyond basic parameters like solar radiation, air temperature, and wind speed, such as precipitation and humidity variations. Overlooks interaction effects between the roof and the internal thermal loads of the building. Surface focus with limited energy savings insight as it provides limited insight into broader energy savings that GRs could offer, such as potential reductions in energy use across different building types.	Shallower soil was found to lower surface temperatures during peak solar radiation, as deeper soil stores more heat. A 50% increase in soil depth resulted in only a 2 °C rise in surface temperature during peak solar radiation. This means that shallower soil layers can help reduce heat accumulation, particularly in hot climates. Plants with larger leaves and lower internal leaf resistance contributed to greater cooling of the GR surface through higher rates of evapotranspiration. This resulted in lower surface temperatures compared to bare soil. On a sunny day, the study found that the surface temperature of a vegetation-covered roof is lower than a bare soil surface. When the solar radiation was reduced by 33%, surface temperatures decreased by about 10 °C during peak solar radiation, causing significant cooling energy savings. Lowering the heat flux conducted into the building, thereby reducing the cooling load during hot periods.	[97]
Polo-Labarrios et al., 2020	Transient mathematical model/finite difference method	Mexico	Warm Climate	Advantages: Quantifies the thermal performance of GRs compared to conventional roofs, demonstrating that GRs reduce indoor temperature fluctuations.	Lowering indoor temperatures by up to 12 °K and reducing the cooling load. Providing thermal insulation, which stabilizes indoor temperatures and reduces temperature fluctuations by up to 14 °K.	[98]

				Utilization of real meteorological data, including solar radiation, ambient temperature, and wind speed, which are readily accessible from weather stations. Application of a transient mathematical model that accounts for heat transfer through the roof and walls of buildings, along with the energy balance inside the building. Highlights the potential for energy savings of GRs by reducing indoor temperatures, beneficial in warm climates, contributing to lower energy consumption and improved thermal comfort. Limitations: Neglects internal heat sources, such as people or electrical devices, which could affect indoor temperature and energy performance. Single climate focus—the warm climate of Mexico City limits its generalizability to other climates, especially cold or temperate regions. Exclusion of precipitation effects, which can affect the thermal performance of GRs through increased soil moisture and evaporation rates.	Providing indoor temperature variability, as a GR causes the indoor temperature to fluctuate between 293 °K and 301 °K (about 20 °C to 28 °C) compared to a conventional roof, where it fluctuates between 291 °K and 313 °K (about 18 °C to 40 °C). This reduced variability directly contributes to thermal comfort and energy savings.	
Ayata et al., 2011	Basic model—genetic algorithm software	Pennsylvania, United States	-	Advantages: Conducted in a controlled environment, allowing for precise measurements of temperature, velocity, and humidity. Comprehensive comparison of different convective heat-transfer models and considering various airflow velocities. Highlighted the importance of parameters such as soil moisture content, vegetation coverage, and leaf area index (LAI) in affecting convective heat fluxes, which are critical for accurate modeling of GR performance. Limitations:	-	[99]

				Limited reflectivity of the complexities of real-world environments, as it is conducted in laboratory conditions. Limited seasonal analysis by focusing only on summer conditions, which may overlook the performance of GRs during other seasons.		
Takakura et al., 2000	Continuous system modeling program (CSMP)	Tokyo	Summer	Advantages: Utilization of both experimental and simulation approaches to evaluate the cooling effects of greenery is needed. A comprehensive analysis was conducted, and greenery cover, concrete, soil layers, and vegetation like turf and ivy were tested. Focus on the impact of the leaf area index (LAI) on enhancing evapotranspiration and cooling effects. Limitations: Adaptation of a small-scale model, which may not accurately represent the heat-transfer dynamics in full-scale buildings.	The ivy-covered roof maintained much lower daytime temperatures (24 to 25 °C) compared to the bare concrete model, which reached nearly 40 °C during the day and fell below 20 °C at night. The ivy-covered surface showed the highest rate, 2.7, which caused its cooling efficiency. The ivy-covered surface showed that surfaces with higher LAI (leaf area index) values of 3.0 exhibited larger effective areas for evapotranspiration, resulting in negative heat loss from the inside to the outside. In contrast, the concrete surface had a positive heat flow, indicating heat gain.	[100]
Santamouris et al., 2007	Mathematical model + TRNSYS	Athens, Greece	Summer and Winter	Advantages: Highlights the GR energy efficiency and environmental benefits. Showcases the heating and cooling load benefits and cost savings linked to the installation of the GR system. Includes a practical investigation and simulation of the GR's performance, providing valuable data that can be implemented in similar cases in urban environments. Supports advancements in building technologies and sustainable practices, encouraging more widespread adoption of GRs in urban planning. Limitations: Focuses on a nursery school building in Athens, Greece, which may not be representative of other building types	The integration of a GR system significantly contributes to energy savings, particularly in reducing cooling loads during the summer months. For the whole building (non-insulated), the cooling load reduction varied between 15% and 49%. For the whole building (insulated), the cooling load reduction ranged from 6% to 33%. For the top floor (non-insulated), the cooling load reduction fluctuated between 27% and 87%. For the top floor (insulated), the cooling load reduction varied from 12% to 76%.	[101]

	or geographic locations. Results derived from the specific case study may not be applicable to different types of buildings, such as residential or commercial structures, that may have varying energy dynamics. Limited physical parameters in the experimental investigations. The study does not account for variations in climate conditions over time, which could affect the long-term performance of the GR system.	

4. Vertical Greenery Systems

4.1. Introduction to Vertical Greenery Systems

History shows that using vegetated facades on buildings is not a new technology, but it can be implemented nowadays to offer multiple benefits as a component of current urban design. Current-day green facades have the potential to be derived from traditional architecture; however, they incorporate advanced materials and other technologies that promote sustainable building functions. As is known, building facades face daily environmental influences, such as sun and acid rain, which age and eventually destroy them permanently; therefore, living wall systems can pose a valuable asset in protecting these facades. Dating back to the 19th century in North American and European cities, the first forms of these greenery systems were woody climbers that were frequently used as a cover for simple facades. The vertical greening system (VGS) is defined as the application of vegetation to vertical surfaces such as facades, walls, blind walls, and partition walls, with the primary objective being the nurturing of plants on building exteriors. Vertical greenery entails the utilization of plants to wholly or partially cover building surfaces directly or indirectly through the employment of metal frameworks or modular planting techniques. Its suitability is contingent upon several factors, such as building design, location, and cost. The VGS can be referred to by various terms, including vertical garden, vertical landscapes, green wall, vertical green, bio-facades, vegetal facades, vertical hydroponics, vertical gardens, and bio-walls [20,23]. However, the most utilized terms are VGS, green walls, living walls, green facades, and facade greening. A unique term pertinent to vertical greenery systems (VGSs) is the double-skin facade. This architectural term denotes using two layers of building skin with an air gap in between, facilitating airflow for insulation purposes. In research on the double-skin facade, plants were incorporated within this space to assess their impact on thermal characteristics and occupant comfort [102]. Based on the planting method, vertical greenery systems (VGSs) can generally be categorized into three types: direct and indirect greening and modular systems. Initial studies predominantly focused on direct and indirect greening, but since 2012, there has been growing interest in research concerning modular greening systems. Early VGS designs primarily prioritized heights and ease of installation, with aesthetic considerations and screening undesirable views being secondary concerns. Presently, the applications of VGSs, particularly in urban settings, have expanded to encompass various economic and practical objectives. Since the 1980s, research has intensified on the advantages of the VGS for the built environment, such as the insulating effects of plants on facades with a specific emphasis on reducing energy consumption, plants' evaporative cooling effects, the ability of plants to mitigate dust, mitigating urban heat island effects, and contributing to the creation of more sustainable urban environments through habitat creation for urban wildlife, including birds, spiders, and beetles [36,103]. Traditionally, a green wall encompasses two distinct systems: green facades and living walls. The main difference between them lies in the natural growth of vegetation over the building envelope, where in a green facade, plants are fixed in the soil on the ground and climb on the facade to cover the elevation.

In contrast, in a living wall, the plants are pre-vegetated sheets and cladding structures that are attached, uniformly covering the building frame [20,23,104]. Unlike green facades, living walls necessitate essential materials such as support elements, growing substrates, and irrigation systems to sustain diverse plant species, leading to notably higher maintenance costs [105]. Yet, in spite of the higher costs associated with them, living walls typically exhibit superior performance due to the utilization of pre-cultivated plants and their ease of transferability. In the case of any unexpected plant-related issues, it is always easier to replace pre-cultivated plants [1].

Even though green facades and living wall systems are both forms of vertical greening, they exhibit distinct differences when it comes to thermal insulation and environmental performance. Green facades target the building's exterior by integrating climbing plants using trellises or cables, creating a natural insulating barrier between the building and its environment. Green facades provide thermal insulation primarily due to the shading effect, which reduces solar heat gain on the building's surface. Studies show that green facades can lower surface temperatures by up to 15–20 °C in warm climates, resulting in a 30–40% reduction in cooling energy demand. However, their effectiveness depends on the plant species, density, and the facade's exposure to sunlight. On the contrary, living wall systems are more advanced, incorporating built-in substrates and irrigation systems that support denser vegetation, which results in a better overall thermal performance. Living walls offer both active cooling through evapotranspiration and passive cooling by creating an additional layer of insulation. The present research suggests that living walls can reduce interior temperatures by up to 8 °C and lower energy consumption by up to 50%, depending on the design and local climate. A thicker plant layer and active water management combination make living walls more effective than green facades when it comes to thermal regulation. By assessing these systems in various climatic conditions, studies have shown that green facades tend to perform better in temperate and arid regions, where their lower maintenance and reliance on natural rainfall provide energy savings without significant irrigation needs, while living walls outperform green facades in hot and humid climates owing to their ability to facilitate greater evapotranspiration, leading to enhanced cooling effects. Furthermore, the higher plant density in living walls enables more biodiversity and better air quality improvement, particularly in urban areas with poor air circulation. In the realm of sustainability, both systems contribute to carbon sequestration, reduced urban heat island effects, and improved stormwater management. Still, the living walls' higher installation and maintenance costs must be weighed against their superior environmental performance. Therefore, the choice between green facades and living walls must consider local climate, building design, and sustainability goals, with living walls generally offering superior performance in challenging thermal environments [102–105].

4.2. Types of Vertical Greenery Systems

Green walls, also called vertical gardens, are traditionally used to refer to all forms of vegetation surface. In order to make the best decision about the most appropriate vertical greening concepts for energy saving, it is crucial to understand the type of system and influential factors for its operation. Presently, all vertical greenery systems can be broken down into two main categories: green facades, also known as the support system, and living walls, also termed carrier systems, and that is based on their establishment method, maintenance, and operation. Figure 5 depicts the breakdown of the two broad greenery systems according to their constructional features [1,20,106].

4.2.1. Green Facades

To begin with, green facades are defined as green walls in which climbing plants or cascading groundcovers envelop the fabricated supporting structures. The plants associated with this type of wall are rooted at the base of these structures, either in the ground or intermediate planters. The plants typically take 3–5 years to attain full coverage [106]. Direct facade greening, also known as the traditional way of greening facades, is a system in which the plants directly adhere to the wall through natural growth or by using the building materials as a support, and they are rooted in the ground or planter boxes. Even though it is relatively simple to adapt and create a lush green facade, one of its characteristics is that climbing plants take a long time to occupy the wall face and can hardly grow up to 25 m without a supporting structure, which calls for more maintenance as they cause facade material deterioration. The indirect facade greening functions as a double-skin green facade, as an air cavity between the facade and the green layer is ensured by specific structural supports such as mesh, wires, or trellis. Plants can be planted in the ground, on the roof, or on substrates attached to the wall [1]. Two types of indirect greening systems exist continuous guides and modular trellis. The former is constructed on a single support structure that spreads the development of plants along the entire surface; the latter is a similar solution but is due to the installation of several modular elements along the surface. The main contrast lies in the fact that modular trellises incorporate vessels for plant rooting and feature individual support structures to guide plant growth. The approach of indirect greening facilitates plant replacement or rearrangement, as it demonstrates flexibility in plant selection and maintenance. It is well suited for buildings with restricted space or structural limitations, enhances the insulating qualities of green walls, protects the integrity of facade materials, mitigates the risk of damage, and promotes accelerated plant growth through structural support [23].

4.2.2. Living Wall Systems (LWSs)

On the other hand, living wall systems (LWSs) are one of the recent advancements in the realm of wall cladding. They are carrier systems composed of pre-vegetated panels, vertical modules, or planted blankets fixed vertically to a structural wall. These panels can be fabricated with a wide range of materials, such as plastic, expanded polystyrene, synthetic fabric, clay, metals, and concrete. The three main components of such a system are the growing substrate media, the carrier that holds the substrate, and its structure. Their main goal is to enable the rapid incorporation of greenery into large, tall structures and promote uniform growth along vertical surfaces accommodating various architectural configurations. Additionally, they accommodate a broader array of plant species. They can be typically categorized as continuous or modular, depending on their mode of application and the growing medium. Continuous living wall systems utilize lightweight and permeable screens that enable the insertion of plants individually. Because of these geotextile membranes, the growing medium is not a requirement [23,106]. Plants in them grow and nourish through irrigation using hydroponic techniques. Conversely, modular LWSs can be designed as planters and panels [11]. The system components include modular components made of plastic, metal, or ceramic, and an encased growing medium placed onto the wall surface isolated from the wall material by a waterproof membrane, irrigated through a drip-feed system. In many cases, living walls are bioengineered, so plant roots are considered a reinforcing mechanism within the wall structure. The modular LWSs can consist of various sub-components, including trays, vessels, planter tiles, and flexible bags. Trays typically feature rigid containers that hold the soil, while vessels are positioned vertically relative to each other. Planter tiles find application both indoors and outdoors within building structures. Finally, flexible bags utilize lightweight materials and can be adapted to surfaces of diverse shapes, including curved or sloped configurations [11,107].

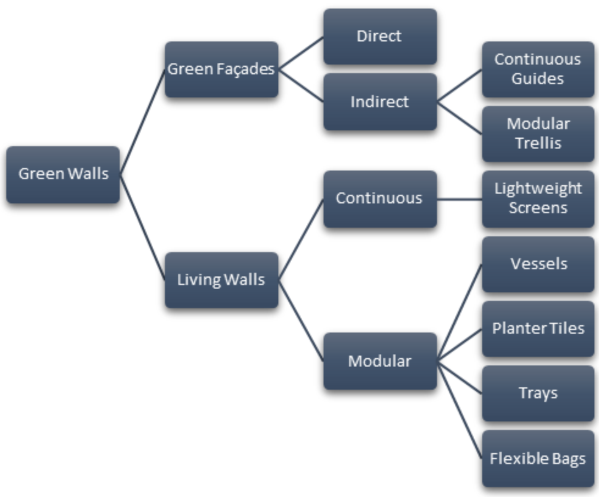

Figure 5. Green wall breakdown and classification.

4.3. *Impact of Green Walls on Energy Performance*

During times marked by escalating environmental concerns and pressing energy challenges, the call for decisive actions to mitigate climate change and enhance energy efficiency has never been more critical. Therefore, resorting to greening systems within various sectors emerges as a promising solution that fosters sustainable development and ameliorates the adverse impacts of usual practices on the environment. With all their technologies and strategies, greening systems target the enhancement of environmental quality while advancing energy efficiency and performance. By embracing these integral synergies between vegetation, building materials, and renewable energy sources, greening systems have great potential to revolutionize the built environment and create resilient, low-carbon communities. At its core, installing and fostering these VGSs within urban landscapes and architectural frameworks pose numerous benefits on different levels, such as enhanced thermal insulation and reduced energy consumption, since a vegetation layer on building facades reduces solar heat gain and enhances natural ventilation. Not only that, but these living walls can contribute to temperature moderation, improve air quality by enhancing indoor environmental quality, mitigate the urban heat island effect by creating cooler microclimates within built environments, and reduce carbon emissions. Their strategic incorporation facilitates natural cooling mechanisms, diminishes heat absorption, and reduces the demand for mechanical heating and cooling systems, thereby leading to considerable energy savings and efficiencies [20,103]. By thoroughly presenting numerous pivotal case studies' numerical and experimental techniques, the following section seeks to clarify the synergies and potential transformative routes associated with incorporating green systems into building facilities in terms of energy sustainability and environmental resilience.

4.3.1. Green Wall Building Energy-Saving Benefits

In a building, the surface that separates the indoor and outdoor spaces of a building is termed the building envelope. It can also be referred to as the building fabric or shell. The energy performance of a building is highly related to this building envelope and its structural properties, which in turn affect the structure's heating and cooling energy performances, and its effect on energy consumption is indisputable. Solar energy is the most potent environmental component that affects buildings both inside and outside, being the world's primary energy source. Buildings and the surrounding environment are kept cooler by adding plants and flora as vertical greenery systems to their surfaces [20]. The concept of vertical greenery systems emerged from the need to enlarge the greened area in urban environments by applying them to building facades, as the horizontal spaces in a building are insufficient to be planted alone in most cases. Thus, numerous researchers declare that the ambient temperature can be reduced by increasing the greened urban area, making the concept of a living wall a key factor. The incorporation of VGSs can significantly lower temperatures around a building by providing shade, thermal insulation, and transpiration cooling [37]. They also offer means to reduce waste heat and consequently lower greenhouse gas emissions while helping to stabilize excessively high ambient temperatures caused by the urban heat island effect. Furthermore, VGSs contribute to improved human health, provide habitats for various species, reduce air pollution, and enhance sound insulation [108]. In summary, VGSs impact energy conservation in buildings through multiple mechanisms: shading, evapotranspiration, thermal insulation, and wind-blocking effects [109]. In their research, Di and Wang [110] evaluated that the average measured surface temperature under a green facade is around 8 °C. It was shown that the maximum temperature reduction was 16 °C compared to the front of the green facade. In the same study, it was found that the west-facing wall received 189 W/m^2 of solar radiation. The leaves reflected and absorbed 28 W/m^2 and 133 W/m^2, respectively, while the remaining solar radiation passed through the leaf layer. The heat fluxes representing average transpiration, thermal convection, and longwave radiation on the building facade are reported to be 42%, 40%, and 18%, respectively. Thus, by growing a traditional green facade, the surface temperature reduction in the cooling seasons ranges between 2 and 16 °C. Susorova et al. [111] assessed the external and internal wall temperatures of a building with a green facade compared to a bare facade temperature. In the covered facade, the temperature difference was found to range between 5.7 °C and 7.9 °C, and there was a decrease in the internal temperature, which was measured to be 0.9 °C. The double-skin green facade has some extra thermal insulation features that grace the air cavity. Wong et al. [112] underlined that the energy transfer through a wall can be reduced by about 0.24 kWh/m^2 through such systems. Consequently, the energy required to operate an air conditioner also decreased by 20%. It was also shown that a reduction of 0.5 °C in room temperature can reduce electricity consumption by 8%, resulting in energy savings. Stec et al. [113] considered the impacts of two types of double-skin green facades, blind and bio-shade facades, on energy demand and surface temperature. Their research concluded that the bio-shade facade's temperature was 20 °C lower than that of the blind facade. On the other hand, a remarkable reduction in cooling demand, reaching up to 20%, was observed [113]. In two of their case studies conducted in Spain under a Mediterranean climatic zone, Perez et al. [114,115] found out that a double-skin green facade caused a temperature drop of 5.5 °C during April to reach a maximum temperature reduction of 15.2 °C. During winter, the temperature of the indoor environment registered a 3.8 °C increase, while in summer, in contrast to traditional walls, the indoor climate underwent a 1.4 °C decrease. In this context, it is safe to say that the double-skin green facade offers higher temperatures and lower relative humidity during winter and lower temperatures and higher relative humidity during summer. This is due to the innate wind barrier and evapotranspiration properties of vertical greenery systems. Also, in Spain, Nori et al. [116] assessed the effectiveness of a living wall system installed on the exterior wall of a highly insulated building during both sunny and cloudy days. One of the main parameters that affected the wall was the intensity of solar radiation. The conventional facade recorded a peak temperature of 46.7 °C when the radiation reached 692 W/m^{2}K on a sunny day, in contrast to the green facade, which registered only 22.1 °C. On a cloudy day, when the solar radiation was only 140.8 W/m^{2}K, the temperature variance between the two facades was only 3.1 °C. Koyama et al.'s [117] work correlated foliage thickness and temperature reductions to assess the associated energy savings. It was shown that by increasing the percentage of foliage between 13% and 54%, a reduction in the range of 3.7–11.3 °C in the external surface's temperature was noted. Their results further proved the effectiveness of greenery surfaces on the thermal regulation of a building envelope. In another work, Chen et al. [118] demonstrated that the external surface temperature and the air layer thickness were inversely proportional, as the reduction in the outer surface temperature decreased with the increase in the air layer. The maximum temperature reduction was around 21 °C, while the interior temperature decreased by 7.7 °C. Moreover, within the interior space, there was a reduction of 1.1 °C, leading to an energy saving of 0.4 kWh compared to the bare wall. Coma et al. [114] tested energy savings through a double-skin green facade and green wall during summer and winter. It was shown that the energy that resulted from incorporating a green wall was more notable than the double-skin facade summer, reaching 58.9% and 33.8%, respectively, in reference to the bare wall. The energy consumption in winter also diminishes by 4.2% through a green wall. In England, Stenberg et al. [119] evaluated the role of ivy (*Hedera helix*) in moderating wall surface microclimates. They found that across all tested sites, the exposed surfaces recorded higher daily maximum temperatures, reaching 36% and 15% lower daily minimum temperatures compared to the ivy-covered adjacent walls. The planted ivy canopy abridged the daily maximum surface wall temperatures to fluctuate between 1.7 °C in Nailsea for a <10 cm-thick ivy cover and 9.15 °C in Oxford for a 45 cm-thick ivy cover. Even when the temperature dropped, the ivy canopy secured the temperature between 0.64 °C in Nailsea and 3.88 °C in Byland with a 20 cm-thick ivy cover, which was higher than the recorded temperature for the exposed wall surface.

4.3.2. Green Walls Modeling and Experimental Testing

In recent years, many efforts have been put into comprehending the dynamics of green walls through modeling approaches. This growing interest is evidenced by a surge in research studies that employ various methodologies, including observational, experimental, and modeling techniques. Green wall modeling and exploratory testing pave a path that facilitates optimization of their design and performance. Combining these approaches generates a comprehensive understanding of these systems and more effective and sustainable implementation in buildings and urban spaces. It maximizes their potential benefits for the built environment [120]. Kontoleon and Eumorfopolou [121] adopted a plant-covered wall thermal network model (PCW model) to compute the temperatures and energy savings for a typical heat-flow path corresponding to a wall surface with a green foliage layer. Aiming to include the plant-covered canopy, this model incorporated the outdoor and indoor environments by including two major subdivisions: the wall model (WM) and the canopy model (CM). The temperature reductions for the exterior and interior surfaces and cooling loads were measured as follows: 1.73/0.65 °C and 4.65% for the north facade; 6.46/1.06 °C and 7.60% for the south facade; 10.53/2.04 °C and 18.17% for the east facade; and 16.85/3.27 °C and 20.08% for the west facade. In another study, Wang et al. [110] based their analysis on a theoretical mathematical model that computed the heat transfer to the leaves and the wall. Their equations calculated the conductive heat transfer and energy use reduction, which are essential criteria related to green walls. It was shown that on summer days, the cooling load transferred through the wall was reduced by 28% and the heating load was reduced by solar radiation absorption, as 40% of the energy that was absorbed by leaves was lost through convection, 42% through transpiration, and the rest through longwave radiation to the environment. Another mathematical model was introduced by Susorova et al. [111] to assess the impact of factors such as leaf area index, average leaf dimension, and leaf absorptivity on a facade's thermal performance by influencing parameters such as the exterior wall surface temperatures and heat flux through the facade. Their model was validated through experimental work that measured the thermal performance of the bare and vegetated facades of a building located in Chicago. After data collection and validation, it was seen that the plant layer caused a decrease in the temperature of the brick facade by 0.7–13.1 °C, thus reducing the heat flux through the exterior wall by 2–33 W/m2 and providing an effective R value of 0.0–0.71 m2 K/W. Stec et al. [113] developed a simulation model built with the use of the Simulink feature in Matlab to describe the thermal performance of a double-skin facade with plants, and the results showed that plants create more effective shading than blinds, since the temperature of the double-skin facade's layer with plants was considerably less than with blinds. The plant's temperature increase due to solar radiation was about half that of the blinds. Installing plants in the double-skin facade reduced the cooling capacity and energy consumption by almost 20%, as the plant's temperature never exceeded 35 °C, while the blinds could exceed 55 °C. The work of Wong et al. [75] involved TAS simulations and thermal calculations to cover the effects of a vertical greenery system's envelope thermal transfer value (ETTV) on both the thermal comfort and energy consumption of a building, respectively. A proportional relationship was found between the shading coefficient and leaf area index. A lower shading coefficient caused better thermal insulation and 50% greenery coverage, while a shading coefficient of 0.041 cut the ETTV of the building facade by 40.68%. It was then concluded that the key behind effective shading is thick greenery, as reductions between 10% and 31% in the energy cooling load were found as an outcome of the greenery. Using their thermodynamic transmission model, Jim and He [122] simulated vertical greenery systems' heat flux and temperature variations and validated the system using experimental methods. Their studied parameters were the heat flux transmission and temperature variations across the walls. The results showed that during peak levels of global solar radiation and temperature on the southern face wall, reductions up to 8.83 °C were recorded.

Cuce's model [19] was modeled on Ecotect software, and simulated the solar radiation distribution on green and bare walls to highlight the shading and thermal insulation features of green walls. Two modeled cases using Nottingham's weather data station verified that green surfaces can absorb a substantial part of incoming solar radiation. Under temperate climatic conditions and using only 10 cm-thick ivy, a temperature drop of more than 6 °C was witnessed. Even for cloudy sky conditions, these reductions were promising, as a decrease of about 4 °C in wall temperatures was achieved. For residences situated in the different climatic zones of the US, McPherson et al. [123] studied the effects of solar radiation and wind speed on energy performance by performing computer simulations using the SPS program and the microcomputer-based energy analysis program MICROPAS. The results showed that in Madison, the annual heating costs required in the cold increased by 28% since the irradiance reductions noticeably increased; however, in the hot climate of Miami, reduced cooling costs reaching 61% were achieved. Dense shading that effectively covered all surfaces significantly decreased peak cooling loads, ranging from 31% to 49%, equivalent to a reduction in energy consumption of 3108 to 4086 watts. Additionally, a 50% reduction in wind speed decreased annual heating expenses by USD 63 (11%) in Madison while simultaneously leading to a USD 68 (15%) increase in yearly cooling expenses in Miami. Feng et al.'s [17] research modeled the energy consumption needed for heating and cooling and conducted detailed energy simulations using DesignBuilder and EnergyPlus software. The derived simulation model was validated using actual building energy consumption data. For a building with a green wall, the heating energy savings were reported to be 0.6% and 2.1% in December and January, respectively. In July, for a conventional building, the cooling demand attained its peak consumption of 52.84 GJ. In contrast, the energy of a building with a green wall was 47 GJ, resulting in 8.4% energy savings. Even though the cooling energy-saving performance was best reflected in summer, green walls contributed to a 7.3% energy saving. Yin et al. [124] used thermal infrared (TIR) and three-dimensional point cloud (3DPC) data as a new methodology to evaluate the cooling effect of a direct green facade on fine-scale plant characteristics during hot summer days. Their case study, conducted at the Executive Office Building on Nanjing University's Campus, showed a 4.67 °C reduction in the surface temperature between the bare wall and the DGF surfaces. The cooling benefits of the green wall were most apparent from 10:30–16:00, while reductions in the surface temperature were not very significant during these hours (<1.5 °C), as shading on the building facade became the dominant factor in facade cooling of the DGF. Malys et al. [125] performed their research using SOLENE-Microclimate simulation software. They aimed to elaborate a new hydrothermal model by developing an efficient coupled heat- and mass-transfer model for vegetated surfaces such as green walls. It was found that a building envelope covered with vegetation could mitigate the urban heat island phenomenon and have a positive impact on the energy consumption of a building. Their model was validated using experimental data collected from three green wall prototypes, which allowed an appropriate understanding of the hydrothermal behavior of the green walls. Holm et al. [126] applied the DEROB system, a dynamic computer model that simulates the thermal effects of vegetation cover on exterior walls of buildings. Their developed model was applied to a standard building in hot and cold weather. It was shown that in summer, the room temperature of the building was reduced by 5°K: from 17 °C–33 °C to 18 °C–28 °C in an ambient temperature range of 21 °C–31 °C. On the other hand, for an outdoor temperature range of 7 °C–18 °C, the indoor temperature was lowered from 10 °C–30 °C without vegetation to 12 °C–27 °C with it. Using a mathematical model to simulate the cooling effects of a green facade, Price [127] determined that a whole-building cooling load reduction oscillated between 1.4% and 28.4% depending on the building construction, green facade placement, and especially the status of the windows. By performing an energy analysis of a south-facing green facade, it was revealed that the total energy consumed could be balanced by the electricity savings from reduced air-conditioning if the cooling load was reduced by at least 14%. Using TRNSYS software, Detommaso et al.[128] investigated the role of a green facade in improving the thermal behavior and indoor conditions of a well-insulated lightweight building. Through their dynamic thermal simulations, it could be concluded that the green facades operated similarly with both plant species when the plants were under full foliage development conditions, implying that the leaf area index greatly influenced the thermal performance of the facade. Based on their setup, the heat flux was lessened by almost 96%, and reductions of 1.6 °C and 10.5 °C were seen in the internal and external surface temperatures, respectively. The research of Thomas et al. [129] in India used the ENVI-met model to compute the efficiency of green walls in the regulation of an urban microclimate in different seasons. The simulation results verified that integrating a green wall into the building morphology could greatly reduce the ambient air temperature, as a decrease of 1.3–1.6 °C was noted during winter and 0.4–0.5 °C during summer, meaning a maximum reduction of 1.9 °C in winter and 0.8 °C in summer. Afshari [130] analyzed the influence of large-scale utilization of an indirect vertical greenery system (VGS) on the cooling demand of a building. In order to assess the thermal interactions between all elements of the tested setting, the building, the VGS, the paved road, and the urban canopy air, a dynamic nonlinear lumped parameter thermal network model was developed using the Simscape toolbox of Matlab. It accounted for both sensible and latent exchanges in and out of the building. In addition, using view factors and the Stefan–Boltzmann law, the short- and longwave radiations were calculated. The outcomes of the study showed that the cooling load decreased by 4.8%, and the wall surface temperature dropped by about 10°C. In another study, Liao et al. [131] established a mathematical model through a numerical simulation to monitor the heat flux transmitted through an ivy-covered wall based on the heat exchanges between the interior surface of the ivy-covered wall and the indoor environment. Next, their model was integrated into the CFD program to execute the simulation. According to their results, a fully covered ivy wall could reduce solar gain by up to 37% compared to a bare wall. Table 3 compiles the many modeling and experimental tests invested in the study of green walls.

Each system holds distinct positive impacts within its technology that enhance urban sustainability and improve the built environment. Green facades play a crucial role in reducing wind exposure and can decrease heat loss by up to 15–25% during colder months, thus contributing to improved energy efficiency in buildings. The leaf surface area provided by the leaves and their layering effect causes the facade to act as a natural barrier against prevailing winds by up to 50%. The thermal mass of the vegetation in these systems can impact local microclimates by altering thermal conditions. The presence of plants can create a buffer zone of warmer air that reduces cold drafts during winter months, which not only protects occupants from harsh weather conditions but also promotes thermal comfort. Additionally, studies have demonstrated that green facades can lower surface temperatures by up to 20 °C, mitigating the urban heat island effect and enhancing biodiversity by providing habitats for various species. In contrast, living walls excel in their ability to provide adequate shading and facilitate evapotranspiration, which is critical for cooling both a structure and its surrounding environment. The evapotranspiration process not only cools the ambient air but also increases local humidity, which enhances overall comfort levels in densely populated urban areas. Furthermore, living walls improve indoor air quality by filtering airborne pollutants, including volatile organic compounds (VOCs), and releasing oxygen through photosynthesis, contributing to healthier living and working environments. Together, these systems have demonstrated the potential to foster climate resilience, promote sustainability, and enhance the quality of life in urban settings [102,106–109].

Table 3. Main green wall simulations and findings.

Authors/Publication Year	Model/ Software	Green Vertical System	Location	Climate/ Period of Study	Advantages/Limitations	Building Energy Performance	Ref.
Feng et al., 2014	DesignBuilder and EnergyPlus software simulation	Green walls	Canada	-	Advantages: Highlights the energy savings in cooling due to green vegetation, as the heat gained through the walls and roof during warmer months is significantly reduced. Highlights heat flux reduction due to the decrease in the negative heat transfer, especially during summer, and the stabilization of internal building temperatures. Focuses on the delayed heat gain as green vegetation delays its starting time by 1–3 h and shortens its period by 5–6 h per day, which reduces the cooling load. Focuses on the green vegetation's environmental benefits such as improved air quality, urban heat island mitigation, and enhanced biodiversity. Limitations: Uncovered green vegetation has limited energy savings in winter, as it is not cost-effective in colder climates due to minimal energy savings during winter. Concluded that green vegetation has high initial and maintenance costs as the cost of installation and maintenance outweighed the energy cost savings. Highlighted the minor impact on well-insulated buildings, as green vegetation may have a more significant effect on older or less insulated buildings.	The integration of GRs reduced annual cooling energy by 3.2%. Its associated annual heating energy savings were minimal (less than 1%). The integration of green walls reduced annual cooling energy by 7.3%, and yearly heating energy savings were 1.6%. In summer, GRs reduced heat gain through the roof by 68% compared to a bare roof. Heat gain was delayed by 1–3 h and shortened by 5–6 h daily, which contributed to reduced cooling loads. In July (hottest month), GRs reduced cooling energy consumption by 5.4%. GRs reduced heat loss by 20% in winter but did not cause significant energy savings due to already well-insulated building facades.	[17]
Cuce 2017	Ecotect simulation	Green walls	Nottingham	Temperate climatic conditions	Advantages: Demonstration of the temperature reduction benefits of green walls, which can reduce internal wall	Green walls caused a temperature reduction of 6.1 °C on sunny days and 4.0 °C on cloudy days compared to a bare wall.	[19]

				temperatures compared to a bare wall, highlighting the potential of green walls in reducing building heat gain. Highlighting the energy-saving potential of green walls by calculating the internal temperatures in warmer climates or during summer. Based on a comprehensive methodology, the study uses both experimental and numerical investigations, providing a reliable approach to understanding the impact of thermal regulation on green walls. Focuses on green walls' environmental advantages, such as improved air quality, noise reduction, and a reduction in greenhouse gas emissions. Limitations: High dependency on the plant type, intensity, orientation, and location, thus significantly affecting temperature reduction. Limited focus on winter energy savings, as it extensively covers thermal regulation during warmer conditions. Study of a specific vegetation type, ivy, and narrow testing conditions, as it was tested in Nottingham's temperate climate.	Green walls achieved a 28% reduction in cooling demand when installed on the west-facing wall of the building, where solar exposure is highest. This underscores the energy-saving potential of integrating green vegetation into building designs, particularly in regions with high solar exposure.	
Wong et al., 2009	TAS simulations and thermal calculation simulation	Green wall	Singapore	-	Advantages: Demonstration of the significant energy savings of vertical greenery systems, highlighting their effectiveness in energy conservation. Illustrates the thermal comfort improvement associated with vertical greenery systems, as they lower the mean radiant temperature of buildings. Utilizes a comprehensive TAS simulation approach that allows a detailed analysis of various scenarios, providing insights into the thermal performance of buildings	Significant reduction in the energy cooling load, as 100% greenery coverage and a low shading coefficient (0.1) achieved a 31.75% reduction in energy cooling consumption. A significant reduction in the envelope thermal transfer value (ETTV), as 50% greenery coverage with a low shading coefficient of 0.041 resulted in a 40.68% reduction in the ETTV of a glass facade building. This demonstrates the	[75]

					with different levels of greenery coverage and shading coefficients. Establishes a linear relationship between the shading coefficient and leaf area index, indicating that lower shading coefficients lead to better thermal insulation. Highlights vertical greenery's ability to mitigate the urban heat island effect, which leads to lower air temperatures in urban areas. <u>Limitations:</u> Limited generalizability, as the study is conducted in Singapore: the findings may not be directly applicable to other geographical locations with different climates, building materials, or urban layouts. It lacks the inclusion of maintenance of greenery, plant growth, and seasonal changes.	potential of vertical greenery systems to enhance thermal performance and reduce heat transfer through building envelopes. Vertical greenery systems result in energy reductions of 50–70% in some cases and a 5.5 °C reduction in immediate outdoor temperatures.	
Wang et al., 1999	Theoretical mathematical model	Traditional green facade	China	Humid continental climate	<u>Advantages:</u> Presents an analysis of the cooling effect of ivy by measuring the heat flux and temperature variations. Comprehensive data collection and experimental validation by measuring multiple parameters, including solar radiation, indoor temperature, heat flux, and relative humidity over two summers (1996 and 1997) at Tsinghua University library. Highlights the energy efficiency potential of the ivy plant in reducing cooling loads in buildings, suggesting a sustainable alternative to traditional air-conditioning systems. <u>Limitations:</u> Specific site locations may limit the generalizability of the results to other buildings or climates with different conditions. Uncertainty in measurements: as the article mentions, the uncertainty of the experiment was not considered.	A reduction in peak cooling load of 28% on a clear summer day was witnessed due to the presence of ivy on the west-facing side. This reduction is crucial for minimizing the energy required for air-conditioning systems. The heat flux of the ivy-covered wall was cut to half compared to the bare wall when the sun was shining. This substantial difference indicates that ivy effectively mitigates solar heat gain, leading to lower indoor temperatures and reduced reliance on mechanical cooling. The leaves of the ivy-covered wall absorbed 133 W/m² of solar radiation, with 40% of this energy lost through convection, 42% through transpiration, and the	[110]

					Focuses on ivy and does not explore other types of vegetation or landscaping that might also contribute to cooling effects.	remainder through longwave radiation. This efficient energy management contributes to lower indoor temperatures and energy savings. Ivy increased the moisture content in the air by 10–20%, enhancing indoor air quality and comfort. This moisture regulation can also reduce the energy required for dehumidification in air-conditioning systems. The ivy layer delayed the peak heat flux through the wall by approximately 8 h. This delay means that the building experiences lower temperatures during peak heat times, which can reduce the demand for cooling during the hottest parts of the day.	
Susurova et al., 2013	Theoretical mathematical model	Traditional green facade	Chicago, USA	-	<u>Advantages:</u> Development of a comprehensive mathematical model of a vegetated wall to evaluate the effects of climbing plants on the thermal performance of a building facade. Permitted the analysis of variable parameters such as weather conditions, climate zones, facade orientation, wall assembly types, and plant characteristics. Verified experimentally with experiments conducted on an educational building in Chicago during the summer. Performed a sensitivity analysis to understand the impacts of different factors like plant characteristics, weather conditions, climate zones, wall assembly types, and facade orientation on vegetated facade thermal performance. Highlights the energy efficiency of the plant layer added to the facade.	On hot sunny days, the plants provided an effective R value of 0.0–0.71 m^2 K/W, depending primarily on wall orientation, leaf area index, and radiation attenuation coefficient. <u>When the incident solar radiation was varied:</u> The plant layer reduced the facade surface temperatures by 0 °C to 13.9 °C. Heat flux reductions through the facade ranged from 0 W/m^2 to 35 W/m^2. Effective plant R value ranged from 0 m^2 K/W with no solar radiation to 0.67 m^2 K/W with the highest level of solar radiation.	[111]

					Limitations: The absence of the soil layer in the developed models focusing on vegetated walls without soil limits direct comparisons and applicability.	When the outside air temperature was varied: Reduction in facade surface temperatures due to the plant layer varied from 12.3 °C to 13.8 °C. Heat flux reduction through the vegetated facade varied from 31 W/m² to 34 W/m². Effective plant R values varied from 0 m² K/W to 0.22 m² K/W. When the relative humidity was varied: Reduction in facade surface temperatures due to the plant layer ranged from 11.9 °C to 14.2 °C. Heat flux reductions through the vegetated facade ranged from 30 W/m² to 36 W/m². Effective plant R values ranged from 0.21 m² K/W to 0.67 m² K/W.	
Stec et al., 2005	Simulink feature on Matlab simulation	Double-skin green facade	-	-	Advantages: Highlights the effective shading system from the plants in the double-skin facade. Highlights the temperature regulation resulting from the presence of plants: the temperature of the layers was significantly lower than with blinds. Emphasizes energy efficiency resulting from the installation of plants, which reduces cooling capacity and energy consumption. Calculation of the ventilation operational time that declined due to the plants' warm periods and increased in cold periods, contributing to energy savings.	When the plants were integrated into the double-skin facade, simulations demonstrated a reduction in the capacity of the cooling system and yearly energy consumption for the building cooling capacity by almost 20% compared to blinds and a corresponding decrease in energy consumption for cooling. The use of plants in the double-skin facade led to a reduction in the operational time of the fan by approximately 10% during warm periods. This indicates improved operational efficiency and potential energy savings.	[113]

					Demonstration of the improved thermal performance of the building incorporating plants in the double-skin facade. Limitations: Missing data on the influence of plants on heating systems: potential for increased demand for heat compared to blinds. Difficulties in determining the properties of the plants, such as the transmission coefficient, could affect the accuracy of the simulation model.	The layer temperature with plants was significantly lower than with blinds, with the plant temperature never exceeding 35 °C, while blinds could exceed 55 °C.	
Kontoleon and Eumorfopoulou 2010	Thermal network model (PCW model)	Traditional green facade	Northern Greece	Warm temperate; fully humid; warm summer	Advantages: Analysis of the influence of orientation and proportion of plant-covered wall sections on thermal behavior. Use of a thermal network model that simulates the building zone effectively. Establishment of several heat-flow paths to consider leaf cover, heat transfer, and natural ventilation. Study of the influence of orientation and covering percentage of plant foliage for walls with different configurations and construction parameters. Validation based on experimental results from a recent study. Identification of the cooling potential of climbers in reducing peak temperatures. Reduction of daily energy requirements of the active thermal zone with a green layer on a wall surface. Limitations: Focus on a specific region (Greek region) during the summer period, limiting generalizability to other climates. Missing potential impact of different plant species or maintenance practices on thermal performance	Temperature differences between the exterior and interior surfaces of plant-covered walls are essentially reduced when compared with conventional bare walls. Temperature variations within the building zone, including plant-covered walls, led to superior thermal comfort conditions. As the percentage of plant foliage covered increased, its positive effect also increased. The influence of a green layer on the wall surface was more pronounced for east- or west-oriented surfaces. The placement of insulation on the exterior surface of masonry led to lower temperature variations. Again, the cooling effect on the exterior and interior surfaces of a plant-covered wall was more profound. The use of vegetation on poorly orientated walls can compensate for their	[121]

					Missing feasibility for the practical implementation of plant-covered wall sections. The impact of long-term maintenance and sustainability of plant-covered wall sections is not discussed.	poor passive design or efficiently reduce the need for cooling loads. The adequate incorporation of a plant-covered wall in a building envelope is shown to be gainful from an energy conservation point of view. It improves and regulates the microclimate around the built environment to a considerable level by neutralizing the solar impact.	
Jim and He 2011	Thermodynamics transmission model + simulation	Green wall	Hong Kong	-	Advantages: Provides a scientific basis for the design and management of vertical greenery systems. Validated experimentally through field measurements to monitor total solar radiation and net radiation. Depicts a numerical model of solar radiation on vertical greenery ecosystems. Explores the impact of vegetation on radiation energy absorption and thermal energy transmission. Limitations: The study acknowledges deficiencies in the model and the need for more elaborate algorithms for accurate computations, indicating areas for improvement. The study focuses on a specific climate (Hong Kong's subtropical climate), limiting the generalizability of the findings to other regions with different climatic conditions.	Vegetation in urban sustainability regulates the energy balance, enhances insulation, and acts as a thermal barrier. Vegetation covering buildings induces cooling of indoor spaces by reflecting and absorbing solar radiation, cooling through evapotranspiration, and providing additional insulation. The vegetative shield created by green walls helps maintain temperature differentials between the interior and exterior of buildings, contributing to energy savings.	[122]
McPherson et al., 1988	SPS and MICRO-PAS simulation	-	Madison, United States Miami, United States	Humid continental climate Hot climate	Advantages: Studies the functioning of whole building systems, integrating building and site to understand the effects of entire landscapes on buildings.	Dense shading of all surfaces in Madison and Salt Lake City increased annual heating costs by USD 128 (28%) and USD 115 (24%), respectively. Moderate shade on all surfaces in Madison increased annual heating costs by	[123]

			Salt Lake City, United States	Mediterranean or dry summer climate	Model effects of modifications to solar heat gains, airflow patterns, and ambient temperatures on building energy performance. Design models to predict the impacts of vegetation and landscape elements on building microclimate and energy use. Limitations: The study did not incorporate all effects of vegetation on building energy performance, limiting the generalization of results to actual designs.	only 10% (USD 59), and light shade increased heating costs by only 3% (USD 14). Dense shade on all surfaces in Miami reduced peak cooling loads by 32–49% or 3108–4086 W Dense shading of all surfaces in Miami reduced cooling costs in hot climates by USD 249 or 61%. In temperate and hot-climate cities, dense shade on all surfaces reduced annual space cooling costs by 53–61% (USD 155–249). A 50% wind reduction lowered annual heating costs by USD 63 (11%) in Madison, but increased yearly cooling costs by USD 68 (15%) in Miami.	
			Tucson, United States	Hot desert			
Yin et al., 2017	Thermal infrared (TIR) and three-dimensional point cloud (3DPC) simulation	Traditional green facade	Nanjing, China	Summer heatwave, July–August	Advantages: Two new models, TIR and 3DPC, provide valuable information to assess the cooling effect of direct green facades at a fine scale. A linear relationship between the percentage of green coverage and the cooling effect of the DGF was identified. Limitations: A specific case study was conducted at the Executive Office Building on Nanjing University's Xianlin Campus, limiting the generalizability of the findings. The study did not explore the long-term effects of DGFs on the thermal environment, indicating a need for further research to assess the sustained impact.	The daily mean surface temperature of direct green facades (DGFs) was significantly lower than the average temperature of bare wall surfaces, with a maximum reduction of 4.67 °C. The DGF's cooling effect was most prominent during 10:30 to 16:00 and decreased significantly at night.	[124]

Malys et al., 2014	SOLENE-Microclimate software simulation	Green walls	Geneva	A mid-season period in a temperate climate	Advantages: Development of a hydrothermal model for vegetated walls using the SOLENE-Microclimate simulation tool. Focus on sustainability and ecological footprints using a natural substrate from local resources. Monitors weather data such as humidity, temperature, and wind speed, which facilitates the analysis of evapotranspiration and microclimate effects. Evaluates three different green wall designs against a bare wall, providing comparative insights into their performance. Gathers data on plant and substrate responses using infrared sensors and flow meters. Limitations: Heavy dependence on solar fluxes may lead to inaccurate predictions, particularly during cloudy conditions. Underestimated peak values: significant peaks in temperature and latent heat fluxes, particularly during irrigation events, are often underestimated by the model. Limited observation period to one mid-season week, which may not capture the full variability of environmental conditions. Underestimation of nighttime cooling effects, which could misrepresent overall thermal behavior.	-	[125]
Holm et al., 1989	DEROB system simulation	Green facade	Southern Africa	Hot arid and Mediterranean climate	Advantages: Utilizes diverse methods that ensure comprehensive data collection. Performs a longitudinal analysis that tracks changes over time, providing insights into long-term trends and effects. Based on a clear methodology that is well outlined and replicable, making it easier for future research to build upon.	The validated model has been applied to standard lightweight building types in hot inland climates, showing that in summer, the leaf cover produces a constant 5 K cooling effect at room temperature of buildings facing the equator. The indoor temperature range was reduced from 17 °C–33 °C to 18 °C–28 °C	[126]

					Fills the gaps present in existing research, offering new insights and informing policy. Propose practical recommendations and actionable suggestions. <u>Limitations:</u> A small sample may limit the generalization of findings. Focus on specific variables may overlook other influential factors. Regional specificity may not apply well to other geographical or cultural contexts.	in an ambient temperature range of 21 °C–31 °C. In winter, the indoor temperature range was reduced from 10 °C–30 °C without leaf cover to 12 °C–27 °C with leaf cover, for an outdoor range of 7 °C–18 °C.	
Price 2010	Theoretical mathematical model	Green facades	College Park, Maryland	Summer—June	<u>Advantages:</u> Focuses on the cooling effects of green facades on various aspects of a building, including ambient environment, exterior wall surface, interior air, and heat flux. Utilizes a small-scale wood-framed building with multiple-species green facades to measure temperature and environmental conditions. Develops a model to calculate the heat flux reduction in one building wall due to a green facade to the whole-building cooling load. Conducts an energy analysis to determine the environmental benefits and energy consumption required for a green facade over its lifetime. <u>Limitations:</u> Lacks information on the thermal benefits of green walls. Limited related research as the majority of published papers on the technology were not available in English.	The integration of green facades significantly reduced the temperature of the building's ambient air, exterior surface, and interior air, as well as the heat flux. The mathematical model determined that the whole-building cooling load reduction ranged from 1.4% to 28.4%, depending on building construction, green facade placement, and window coverage. The energy analysis of a south-facing green facade revealed that the total energy consumed could be balanced by the electricity saved from reduced air-conditioning if the cooling load was reduced by at least 14%. The study emphasized that with thoughtful design and placement, a green facade can sustainably and effectively help cool buildings.	[127]
Detommaso et al., 2023	TRNSYS simulation	Green facades	Catania, Italy	Mediterranean climate	<u>Advantages:</u>	The green facades reduced indoor air temperature and internal surface	[128]

					Analysis of the potential of green facades to improve indoor temperatures during summer through experiments and simulations. Validated by a monitoring campaign, showing strong alignment between real-world data and simulations. Comparisons of different plant species and their leaf area index (LAI), highlighting their impact on thermal performance. Demonstrates green facades' ability to reduce surface temperatures and incoming heat with various plants and LAI values. Provides valuable insights into the cooling effects of different plant species in Mediterranean climates. Limitations: Focuses only on the Mediterranean region, making it less applicable to other climates. Neglects factors like wind speed, humidity, or building orientation, which could affect performance. Lacks the identification of the role of the wall assembly behind the vegetation layer, which could impact performance.	temperature by up to 1.0 °C and 1.1 °C, respectively, during the hottest hours. The green facade with Trachelospermum Jasminoides and an LAI of 2.0 m2/m2 reduced the maximum internal surface temperature on the west-facing wall by 1.1 °C and the external surface temperature by 7.4 °C. The green facade configuration reduced the peak of the incoming heat flux by 78%. The green facades diminished the incoming heat flux by around 96%, resulting in a reduction of 1.6 °C in internal surface temperature and 10.5 °C in external surface temperature.	
Thomas et al., 2023	ENVI-met model simulation	Green walls	India	Humid tropical climate	Advantages: Development of the ENVI-met model that effectively shows how green walls can reduce air temperatures in humid tropical climates and simulates hourly temperature variations, emphasizing the importance of shading. Demonstration of the significantly lower air temperatures during both winter and summer due to the green walls. Highlights varying levels of temperature reduction and identifies the maximum cooling effect of green walls. Emphasizes the role of shading in improving the urban thermal environment and microclimates.	The ambient air temperature showed relatively lower temperatures during the winter (0.2–1.4 °C) and summer seasons (0.1–0.5 °C) compared to other substrates. The ambient air temperature during the afternoon hours (14:00–16:00) showed a maximum difference (compared to other surfaces) during the winter (1.3–3.1 °C) and summer seasons (0.8–2.1 °C). The results of the ENVI-met simulations indicate that the implementation of	[129]

					Limitations: Lacks specific characteristics of plant species, especially in climates with seasonal changes. Bypasses are some of the factors affecting thermal comfort and microclimatic shifts in urban areas. Further research is required to address all concerns about implementing green walls in humid tropical climates beyond the model's scope.	green wall building morphology could significantly reduce the ambient air temperature during winter (1.3–1.6 °C) and summer seasons (0.4–0.5 °C), but with differing intensities. Green walls exhibit a maximum reduction in ambient air temperature by 1.9 °C during the winter and by 0.8 °C during the summer.	
Afshari 2017	Simscape toolbox of MATLAB model	-	Abu Dhabi, UAE	Arid desert climate	Advantages: Confirms the link between urban heat islands (UHIs) and building cooling loads. Demonstrates that vegetated green spaces (VGSs) can significantly reduce UHI intensity and cooling demands in urban areas. Provides new insights into how various factors affect UHI mitigation and energy use, helping understand model sensitivity. Utilizes various convective heat-transfer coefficient (CHTC) models to ensure accurate and reliable results. Limitations: Challenges in maintaining consistent accuracy due to the many empirical parameters used in urban energy models. Assumes full irrigation and no stomatal resistance; hence, it may overestimate the cooling effects of VGSs.	Vertical greenery systems (VGSs) in urban areas significantly reduced cooling load by 5–8%. VGSs significantly reduced urban air temperature by approximately 0.7–0.9 °C. The reduction in cooling load and the decrease in urban air temperature contributed to lowering the intensity of urban heat islands (UHIs) by almost half. Comparison between urban and rural base cases (without VGSs) showed a cooling load penalty of about 7% due to UHIs, emphasizing the importance of VGSs in mitigating this effect. VGSs significantly reduced air temperature and wind speed near walls, showcasing their positive impact on UHI intensity and cooling demand. The study highlighted the effectiveness of VGS in converting sensible heat to latent heat through evaporation and transpiration from VGS foliage.	[130]

Zaiyi et al., 2000	CFD program simulation	Living walls	Hong Kong	-	Advantages: Develops a mathematical model to assess the thermal behavior of ivy-covered walls. Couples and integrates the model with a CFD program for simulation. Identification of key factors influencing ivy-covered walls' ability to reduce cooling loads. Highlights three important design parameters: green density, covering ratio, and the geometry of the supporting grid. Limitations: Simplifies certain parameters, such as the height of the supporting grid, which may affect accuracy. Lacks an experimental system, which is needed to verify simulation results.	Ivy-covered walls (ICWs) considerably reduce the heat flux through external walls, leading to a reduction in cooling load for buildings. Ivy coverings can reduce solar loads by up to 30%, indicating a significant decrease in heat absorption. A fully covered ivy wall could reduce heat flux through external walls by three-quarters, showcasing a substantial reduction in heat transfer. Ivy coverings convert over 70% of the solar energy they absorb into bioenergy via photosynthesis without significantly increasing their temperature, resulting in lower longwave radiation between foliage and external wall surfaces. An ICW with a covering ratio greater than 30% can reduce solar gain by up to 37%, demonstrating a significant cooling effect.	[131]

5. Discussion

In the age of sustainable urban development, green roofs and facades stand as innovative solutions directed at revolutionizing building energy performance and environmental awareness. In one of the United Nations reports published in 2017, it was stated that building construction and operations contributed to more than 36% of the total global energy consumption and around 39% of energy-related carbon dioxide (CO_2) emissions. This article is developed based on a thorough exploration examining the intertwined dynamics and scientific details of the implementation and integration of green infrastructure into the architectural landscape. This review assesses a diverse range of case studies covering residential, commercial, and institutional buildings such as nursery schools and offices, as well as a variety of climatic regions. Through a detailed examination of the complex interactions between climatic influences, architectural typologies, and vegetative characteristics, green roofs and facades have been shown to attenuate thermal fluctuations and significantly reduce energy demand. For instance, studies in temperate climates have demonstrated reductions of up to 20% in annual energy consumption for cooling and heating. At the same time, in tropical regions, green roofs have been shown to reduce peak indoor temperatures by as much as 6 °C, offering substantial energy savings. The review incorporates results from multiple sophisticated modeling techniques, including thermal dynamic simulations with TRNSYS, EnergyPlus, and MATLAB, as well as environmental modeling with FASST, FFT, and Newton's iterative algorithm. These models have been crucial in quantifying the thermal performance of green roofs and facades, highlighting the latter's role in improving insulation properties, minimizing heat transfer, and optimizing indoor temperature regulation. In temperate and tropical climates alike, empirical data and simulation outputs consistently show that green vegetation on building envelopes can reduce heat flux through the roof by as much as 70%, drastically decreasing energy demand for air-conditioning and heating systems. Additionally, modeling studies using ENVI-met have underscored the microclimatic benefits of green infrastructure, such as mitigating the urban heat island effect by lowering ambient temperatures in cities by up to 2 °C while also enhancing urban air quality by filtering particulate matter and absorbing CO_2.

However, despite these apparent advantages, several challenges impede the widespread adoption and implementation of these green systems. One major obstacle is the significant initial investment required for installation, especially in the context of retrofitting existing buildings. These modifications can increase upfront costs by 20–30%, depending on the building's age and structural capacity. Furthermore, long-term maintenance presents another challenge, particularly in regions with extreme climatic conditions, where the durability of vegetation can be compromised. For example, drought-resistant plants may be required in arid climates, while in areas with heavy precipitation or freezing temperatures, specialized drainage systems and frost-resistant plants may be necessary to ensure the longevity of green roofs. Maintenance costs can increase by 10–15% annually in such conditions, reducing the net financial benefits of energy savings over time. Another challenge lies in the limitations of current modeling techniques. While sophisticated models such as FASST and ENVI-met provide valuable insights into the thermal and environmental performance of green roofs and facades, their application on an urban scale is still constrained by computational limitations and a lack of real-world validation. Many models are calibrated using controlled experimental setups or small-scale field observations, which may not capture the full complexity of large-scale urban environments. For instance, the models often overlook factors such as local wind patterns, humidity levels, or variations in plant health, which can significantly affect the performance of green roofs and facades in different climates. Field validation studies across diverse geographical regions are therefore essential to refine these models and ensure their accuracy in predicting the large-scale impacts of green infrastructure. Moreover, the lack of standardized guidelines and regulations for their design, installation, and maintenance presents a significant barrier to their broader adoption. While some cities have introduced incentives or regulations for green infrastructure, these efforts are often inconsistent and lack uniformity across regions. For example, European cities like Paris and Copenhagen have implemented mandatory green roof policies for new commercial and residential buildings, yet such regulations are far less common in other parts of the world. Without a standardized framework, it becomes challenging to ensure consistent performance and efficiency of green infrastructure, leading to varied outcomes in different regions.

Future research should focus on addressing these challenges by improving the cost-effectiveness of green infrastructure, particularly in retrofitting older buildings. Advancements in lightweight, durable materials, such as composites and synthetic substrates, could reduce the structural reinforcement required for installation, thereby lowering up-front costs. Additionally, developing region-specific plant species that are better adapted to local climatic conditions could minimize maintenance requirements and increase the longevity of green roofs. Finally, standardizing regulations and guidelines for green infrastructure is essential for fostering consistent, widespread adoption. Establishing uniform protocols for plant selection, installation, and maintenance would provide clearer pathways for cities and developers to integrate green infrastructure into urban planning, maximizing its potential for reducing energy consumption and environmental impact.

6. Conclusions

Given the ongoing exponential trends in population growth, pollution, and climate change, it has become imperative to address the resultant negative impacts, including energy insecurity, environmental degradation, resource depletion, and the widening social and economic disparities. It has become a consensus that the integration of plantations and greenery systems on the building envelopes will provide a sustainable solution and will address unsustainable energy consumption. The presence of plantations on green roofs plays a pivotal role in altering local microclimates, primarily through the process of evapotranspiration. This natural mechanism significantly contributes to the humidification and cooling of the ambient air in urban environments, effectively mitigating the urban heat island (UHI) effect. An analysis of the interaction between incoming solar radiation and the components of a green system reveals a complex energy exchange process. Specifically, approximately 27% of the incoming solar radiation is reflected into the atmosphere by the vegetative systems. The vegetation and substrate layer collectively absorb about 60% of this radiation. The remaining 13% penetrates through the substrate layer, contributing to a lesser extent to the thermal dynamics of the system. This elaborate balance of reflection, absorption, and transmission results in a significant reduction in solar heat gain, estimated to range between 70% and 90% during the summer months. Concurrently, during the winter period, the green roof system effectively decreases heat loss from the building envelope by approximately 10–30%. These figures underscore the significant potential of these green roofs and facades in enhancing building energy efficiency, thereby contributing to the broader goals of sustainable urban development.

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Abbreviations

ANFIS	adaptive neuro-fuzzy inference system
BREEAM	Building Research Establishment Environmental Assessment Methodology
CO_2	carbon dioxide
CSMP	continuous system modeling program
DB	DesignBuilder
BEE	buildings’ energy efficiency
ETTV	envelope thermal transfer value
EU	European Union
EPS	expanded polystyrene
GBL	Green Building Label
GRs	green roofs
GHG	greenhouse gas
LEED	Leadership in Energy and Environmental Design
LAI	leaf area index
LWS	living wall system
ML	machine learning
NZEBs	nearly zero-energy buildings
TIR	thermal infrared
3DPC	three-dimensional point cloud
UK	United Kingdom
UN	United Nations
USA	United States of America
UHI	urban heat island
VGS	vertical greening system
XPS	extruded polystyrene

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