

Enhancing Urban Sustainability through Green Roofs: A Comprehensive Review of Carbon Sequestration and Energy Efficiency

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Abstract

Green roofs have gained prominence as sustainable solutions to urban challenges, addressing climate change, urban heat effects, and the need for enhanced energy efficiency. This review evaluates how green roofs contribute to urban sustainability by examining their dual roles in carbon sequestration and energy efficiency. The objectives are to synthesize empirical evidence on vegetation- and substrate-driven carbon dynamics, assess the extent to which green roofs reduce building energy demand, and identify the environmental and policy conditions that shape their performance. A PRISMA-based systematic literature review was used across five major databases to examine green roofs' carbon sequestration and energy-efficiency benefits. From 3,000 records, 80 peer-reviewed studies met the inclusion criteria. Thematic analysis synthesized evidence on carbon dynamics and thermal performance, though language and database limitations remain. Findings reveal that green roofs deliver measurable environmental benefits. Vegetation species such as *Sedum acre* and *Frankenia thymifolia* directly sequester atmospheric carbon, while substrate microbial processes enhance long-term carbon storage. Indirect carbon reductions stemming from lower energy demand often exceed direct sequestration. Green roofs also lower cooling loads by up to 70%, reduce indoor temperatures significantly during peak heat periods, and contribute to urban heat island mitigation. Performance varies according to vegetation type, substrate depth, seasonal conditions, and maintenance practices. The study concludes that green roofs hold substantial potential for climate-responsive urban development. It recommends stronger policy frameworks, targeted financial incentives, standardized performance metrics, and expanded research on substrate science. Integrating green roofs into broader green infrastructure networks and ensuring equitable access, especially for vulnerable communities, will further enhance their sustainability impact.

Introduction

Urbanization has significantly altered natural landscapes, contributing to increased carbon emissions, elevated surface temperatures, and compromised environmental health [1, 2, 3]. As cities expand, the demand for sustainable solutions to mitigate carbon footprints and enhance energy efficiency becomes critical. Green roofs have been proposed as an efficient and practical tool to combat urbanization in many countries [4]; this intervention is capable of addressing these challenges. By integrating vegetation into architectural design, green roofs offer dual benefits: carbon sequestration [5, 6] and enhanced energy efficiency [7, 8], thereby promoting urban sustainability [9].

The concept of green roofs is not entirely new; it dates back to ancient civilizations, such as the Hanging Gardens of Babylon [10, 11]. However, modern green roofs have evolved significantly, incorporating advanced materials and designs that optimize their ecological benefits [12, 13]. Green roofs are typically categorized into two types: extensive and intensive; there is semi-intensive too. Extensive green roofs are lightweight and low-maintenance, primarily focused on environmental benefits, while intensive green roofs support a wider range of plant species and require more maintenance [12]. The rise of green roofs

reflects a shift toward sustainable city development, emphasizing ecological preservation [14], energy savings [15], and climate resilience [9].

Despite the proven benefits of green roofs, lack of interest from building owners and clients may lead to limited demand for green roofs, thereby hindering their implementation [16]. Moreover, while substantial research highlights the environmental benefits of green roofs, there is a need for a more focused exploration of their contributions to carbon sequestration and energy efficiency in high-density urban areas. Understanding the extent to which green roofs can reduce urban carbon emissions and improve building energy efficiency is crucial for enhancing urban sustainability strategies.

While numerous studies have examined green roofs' ecological contributions, gaps remain in quantifying their carbon sequestration capabilities and energy-saving potential in diverse urban contexts [17]. Studies have predominantly focused on their aesthetic and stormwater management benefits [18, 19, 20]. But empirical evidence on long-term carbon storage and energy reduction metrics of green roofs is yet to receive wide scholarly attention.

Recent studies indicate that green roofs contribute to carbon sequestration through photosynthesis and soil carbon storage [6, 21]. Additionally, they enhance energy efficiency by providing thermal insulation, reducing the need for artificial heating and cooling [20, 22]. In climates with significant seasonal variation, green roofs can mitigate heat island effects and lower energy consumption during peak weather conditions [23, 24].

The primary aim of this paper is to highlight green roofs' dual role as carbon sinks and energy-efficient systems, emphasizing their proven capacity to sequester carbon while reducing building energy demands and associated emissions and enhancing energy efficiency. This study will synthesize existing literature, present evidence-based analysis, and propose strategic recommendations for maximizing the ecological and energy benefits of green roofs in urban environments.

Literature Review

2.1 Green Roofs and Biodiversity: Supporting Urban Ecology

As global urbanization intensifies, cities are increasingly confronted with complex environmental challenges that threaten ecological balance and human well-being. Among the most pressing concerns are biodiversity loss [25, 26], climate-induced flooding [27], and the intensification of urban heat island (UHI) effects [28, 29]. These issues are exacerbated by the rapid conversion of natural land to impervious urban surfaces, which reduce green cover and fragment natural habitats. In response to these challenges, green infrastructure particularly green roofs has gained attention for its potential to enhance urban sustainability by simultaneously addressing environmental degradation and promoting ecosystem resilience.

Beyond their well-documented roles in energy efficiency and carbon sequestration, green roofs are increasingly recognized as critical components of urban ecological networks and climate adaptation frameworks [20, 30]. By integrating layers of soil and vegetation onto building rooftops, green roofs help restore lost ecological functions within densely built environments.

One of the most compelling ecological benefits of green roofs is their ability to enhance urban biodiversity. By converting otherwise barren rooftops into vibrant green spaces, they support a wide range of plant species and provide habitat for birds, insects, and other small fauna [31, 32]. These systems act as stepping stones or ecological corridors, facilitating the movement of pollinators and improving habitat connectivity across fragmented urban landscapes [33]. Furthermore, evidence from long-term ecological monitoring indicates that green roofs not only attract biodiversity but can also sustain it over time, making them valuable sites for observing species dynamics, succession, and broader ecological changes [34].

2.2 Addressing Urban Resilience and Climate Adaptation through Green Roofs

In addition to their ecological benefits, green roofs play a vital role in enhancing urban resilience to a variety of climate-related stresses. As cities face increasing risks from extreme weather events, the capacity of green roofs to absorb, retain, and delay stormwater runoff has become especially important. This function helps to mitigate urban flooding, reduces surface runoff volumes, and alleviates the strain on often-overburdened municipal drainage and stormwater systems [35]. By acting as natural sponges during heavy rainfall events, green roofs help prevent waterlogging and protect infrastructure.

Furthermore, their vegetative layers provide evaporative cooling, which contributes to reducing ambient temperatures on rooftops and in surrounding urban areas. This cooling effect is especially critical during prolonged heatwaves and periods of intense solar radiation, helping to counteract the urban heat island effect that exacerbates discomfort and health risks in densely populated areas [36].

When integrated into broader climate adaptation and urban planning strategies, green roofs offer more than just environmental value. They contribute to the resilience of urban infrastructure, promote thermal comfort, and support social well-being. As such, they are increasingly recognized not only as sustainable architectural features but as multifunctional assets that deliver long-term climate adaptation co-benefits [9].

2.3 The Science of Carbon Sequestration in Green Roof Ecosystems

Green roofs have gained traction as nature-based solutions capable of mitigating climate change through carbon sequestration. The science of carbon capture in green roof systems is complex, involving

the interplay of vegetation-based photosynthesis, soil carbon dynamics, and microbial activity. Together, these mechanisms enable both short-term carbon uptake and long-term storage, though their efficiency remains highly dependent on biophysical, climatic, and maintenance-related variables.

Central to the sequestration process is photosynthesis the uptake of atmospheric CO₂ by rooftop vegetation. Studies such as [6] provide empirical data on species-specific carbon absorption, revealing that plants like *Sedum acre*, *Frankenia thymifolia*, and *Vinca major* offer optimal performance in both carbon uptake and energy savings. The annual CO₂ absorption rates recorded were 0.14, 2.07, and 0.61 kg/m² respectively, while corresponding reductions in building-related CO₂ emissions due to decreased energy demand were 28.16, 26.48, and 23.44 kg/m². These findings highlight a dual benefit: direct carbon uptake via biomass growth and indirect emission reduction through improved building efficiency.

[37] provide a comprehensive synthesis of the mechanisms and influencing factors of carbon reduction in green roofs. Their review distinguishes between direct absorption (CO₂ captured by vegetation and substrate) and indirect reduction (lower energy consumption). The authors emphasize the need for better modeling approaches and a deeper understanding of spatial variability in green roof performance. Similarly, [38] quantified the net photosynthesis rate of selected rooftop vegetation, while [39] explored sequestration during early stages of green roof establishment yet both studies note the need for long-term assessments of vegetation maturity and seasonal fluxes, which remain underexplored in current literature.

Beyond vegetation, substrate or growing medium serves as a crucial component of carbon storage. Soil acts not only as a physical support for plant growth but also as a carbon sink. Practices adopted from agricultural systems, such as cover cropping and continuous organic inputs, are known to improve soil carbon retention [40]. Yet, applying these principles to green roofs remains largely conceptual, with limited long-term empirical data.

[41] discuss evolving definitions of soil carbon lifespan and critique the disconnect between scientific findings and policy assumptions. While policymakers often consider soil carbon as vulnerable and short-lived, recent studies highlight microbial transformation as essential for the persistence of soil organic matter. This calls for a paradigm shift in how green roof soils are designed and evaluated, prioritizing not just carbon input but its stability and turnover. [42], in a land-use focused study, further illustrate how carbon sequestration potential varies with soil type, elevation, and vegetation. Their spatial modeling approach provides a valuable methodological reference for urban rooftop ecosystems, though urban-specific models remain scarce.

A critical but underrepresented component of green roof carbon science is soil microbiology. Soil microbes including fungi and bacteria play pivotal roles in carbon stabilization. [43] noted the contribution of microbial biomass and exudates such as glomalin to the formation of stable soil carbon pools. Similarly, [44] identified microbial groups that support carbon sequestration, highlighting arbuscular mycorrhizal fungi and melanising endophytic fungi for their roles in transitioning carbon from labile to recalcitrant forms. The review also proposed the promising “biochar + microbe” strategy, which

combines stable carbon input with biological enhancement, yet this approach has not been tested extensively in green roof contexts.

While existing literature has advanced our understanding of plant-based CO₂ uptake and energy savings, it is clear that green roof carbon science remains fragmented. However, there is a particular need for longitudinal studies on vegetation carbon capture over multiple growth cycles, experimental data on substrate amendment and carbon turnover, and integration of microbial ecology into carbon modeling for green roofs. Addressing these gaps will enable a holistic understanding of how green roofs function as effective carbon sinks and will support more evidence-based policy and design standards for climate-resilient urban infrastructure.

2.4 Quantifying Carbon Sequestration Potential in Urban Roofscapes

Recent studies employ a range of techniques to estimate carbon sequestration in urban vegetative systems, including remote sensing, direct biomass sampling, and carbon flux monitoring. [45], in a high-resolution remote sensing study conducted in Luohe, China, quantified the carbon sequestration capacity of urban green spaces at 1.30 t·C·ha⁻¹·yr⁻¹, highlighting the utility of satellite-derived data in assessing landscape-level variations. Meanwhile, [46] used dry-weight measurement techniques to estimate biomass carbon stocks in urban shrubs in Finland. Their approach involved separating above- and below-ground biomass and evaluating size indices (SIs). While SIs were predictive of total dry weight, they fell short in estimating below-ground biomass for species with rhizome networks. These findings suggest that although SIs may serve as useful proxies, they cannot fully capture the below-ground carbon dynamics, underlining a methodological gap in comprehensive biomass accounting.

A growing body of literature has compared the carbon sequestration potential between extensive and intensive green roof systems. [47] determined the carbon payback time for extensive green roofs to range between 6.4 and 15.9 years, depending on the plant species employed. Intensive green roofs (IGRs), however, have demonstrated higher carbon capture efficiencies due to deeper substrates and greater plant biomass, as observed in foundational work by [48].

[49] extended this comparison by conducting year-long carbon flux monitoring and building energy simulations on a newly constructed intensive green roof. They found that the Green Roofs as Urban Carbon Sinks: Modeling and Forecasting total annual CO₂ reduction reached 4355.6 g CO₂·m⁻², with indirect reductions accounting for the majority (4309 g CO₂·m⁻²) and direct sequestration contributing 46.6 g CO₂·m⁻². Seasonal trends were also evident, with peak direct reductions in autumn and maximum indirect reductions during summer. This stark contrast between direct and indirect CO₂ reductions draws attention to the importance of system-wide evaluation, including the role of energy savings in carbon offsetting.

Furthermore, [50] utilized five years of observational data to calibrate and validate a photosynthesis module for green roofs. Their model accurately reproduced the Net Ecosystem Exchange (NEE), affirming the potential of city-scale simulations to project carbon sequestration from green roof interventions. However, model sensitivity to daily variability poses a challenge to high-resolution forecasting, revealing the need for enhanced temporal modeling techniques.

Seasonality plays a critical role in modulating carbon fluxes in green roof ecosystems. [51] emphasized that seasonal changes in CO₂ exchange govern the strength and variability of terrestrial carbon budgets. [52] further demonstrated how meteorological shifts from late May to mid-July significantly affected net ecosystem productivity (NEP) in forest ecosystems, primarily through variations in ecosystem respiration (RE) rather than gross ecosystem productivity (GEP). These findings have direct implications for green roofs, where shifts in temperature and moisture can drastically alter carbon dynamics. Despite this, few urban studies have deeply investigated seasonal physiological responses in green roof vegetation, leaving a crucial gap in understanding temporal flux variability.

Despite notable advancements, several research gaps persist. First, there is a methodological disconnect between remote sensing estimates and direct measurements, particularly concerning below-ground biomass and root architecture in urban roof ecosystems. Second, the long-term carbon sequestration potential of intensive green roofs remains underexplored, especially under climate variability and maintenance regimes. Third, while modeling efforts like those by [50] offer promising pathways for scaling, current models require refinements to capture short-term flux volatility more reliably. Lastly, seasonal physiological responses of roof vegetation are insufficiently quantified, especially in tropical and subtropical cities, which Green Roofs as Urban Carbon Sinks: Modeling and Forecasting host distinct phenological patterns.

2.5 Green Roofs as Urban Carbon Sinks: Modeling and Forecasting

Recent advancements in predictive models underscore the potential of green roofs in reducing building energy demands, particularly in dense urban environments. Modeling studies indicate that green roofs consistently generate energy savings across daily, monthly, and annual timescales, with projections showing increased efficiency under future climate conditions. These energy savings primarily affect heating, ventilation, and cooling systems, with differential outcomes based on building typologies. Notably, commercial structures like shopping malls exhibit the highest savings during extreme summer temperatures.

[53] introduced a Geographic Information System (GIS)-based framework to quantify reductions in greenhouse gases and air pollutants, integrating spatial analysis to assess building suitability for green roof retrofitting. This innovation enables urban planners to visualize pollutant reduction potential alongside locational attributes, contributing to a nuanced, data-driven urban greening strategy.

Additionally, synthesis of 28 international case studies reveals that green roofs can reduce surface temperatures by up to 30°C and retain over 51% of annual rainfall, offering crucial co-benefits such as urban heat mitigation and stormwater management [54]. These findings affirm the environmental value of green roofs, while also indicating the need for dynamic models that incorporate climatic variability, vegetation types, and rooftop configurations to enhance forecasting accuracy. While GIS-based and climatic models offer valuable insights, limited attention has been given to integrating real-time remote sensing data and machine learning techniques for predictive modeling of carbon sequestration outcomes across diverse climatic zones.

Estimating the macro-scale impact of green roofs requires robust greenhouse gas (GHG) accounting frameworks. [55] review the evolution of city-scale emission inventories, noting a transition from Intergovernmental Panel on Climate Change (IPCC) protocols to more tailored methodologies adapted to urban contexts. A significant portion of literature remains focused on proposing customized frameworks that respond to the data availability and socio-technical conditions of specific cities.

[56] examined carbon emissions linked to household travel behaviors across 47 Japanese cities. They found that high carbon footprints often correlate with low population densities, and that transportation modes such as gasoline vehicles and trains heavily influence regional emission patterns. Their findings underscore the importance of developing localized, behavior-sensitive mitigation strategies.

A similar city-level analysis in Chiang Mai, Thailand, applied the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC) to evaluate policy feasibility. Results identified residential, commercial, and industrial sectors as primary emitters, with measures such as LED lighting and efficient HVAC systems emerging as cost-effective interventions [57]. This demonstrates the practicality of energy-efficient retrofits green roofs included as levers for urban carbon mitigation. Although promising, current city-scale modeling approaches often underutilize the spatial and vertical complexity of urban landscapes, such as the cumulative impact of green roofs across building typologies, elevations, and material thermal properties.

Green roofs not only deliver biophysical benefits but also hold economic and policy relevance. Emerging evidence links carbon reduction technologies like green roofs to the performance of Emissions Trading Systems (ETS), green innovation, and equity outcomes.

[58] evaluated China's carbon ETS and found an 8.11% reduction in urban-rural income inequality, particularly in high-emission and affluent cities. [59] extended this analysis, revealing that the ETS significantly fostered urban green innovation, enhanced public environmental awareness, and spurred technological investment. These effects also exhibited spatial spillovers, influencing cities beyond the direct scope of policy implementation.

Further, [60] identified positive spatial autocorrelation in green transition development (GTD), suggesting that policy interventions such as carbon markets not only improve local sustainability but propagate regional benefits. Supporting this, [61] observed a significant spillover effect of green credit on

surrounding municipalities' carbon emissions, indicating that decentralized greening efforts like green roofs can yield systemic benefits.

Despite these encouraging findings, few studies explicitly link green roof adoption to carbon credit quantification frameworks or assess their monetization potential within ETS and green bond markets. There is also a lack of policy guidance on how municipalities can integrate green roofs into verified carbon standard protocols.

2.6 Enhancing Energy Efficiency through Thermal Regulation

Thermal insulation remains one of the most effective passive strategies for improving energy efficiency in buildings. The mechanisms by which insulation reduces energy consumption rely on the ability of materials to resist heat flow, thereby minimizing thermal exchange between indoor and outdoor environments. [62] outlined a wide spectrum of thermal insulation materials, ranging from naturally occurring fibers to advanced cellular plastics, reflective systems, evacuated systems, and aerogels. Each category presents distinct thermal properties and environmental implications.

Recent studies have emphasized the need for innovation in insulation technology. [63] highlighted that many commonly used insulation materials suffer from inherent limitations such as thermal degradation, moisture sensitivity, and limited sustainability. This calls for the development of composite materials that integrate sustainable components with high-performance elements like aerogels.

Nanocellulose aerogels have emerged as a promising material due to their low thermal conductivity and renewable origin. However, [64] identified challenges such as poor mechanical properties, high flammability, and significant water absorption, which hinder their wide-scale application. [65] added that various influencing factors ranging from material composition to installation techniques exert diverse effects on insulation performance and energy efficiency, thereby necessitating further research into optimizing material and structural configurations.

Green and cool roofs have gained prominence as key strategies in mitigating urban heat islands (UHIs), reducing thermal loads on buildings, and improving microclimate conditions. In a comparative study conducted in a tropical context, [66] revealed that cool roofs reduced heat gain more effectively than green roofs during peak periods 0.14 KWh/m^2 versus 0.008 KWh/m^2 , respectively. On a daily scale, cool and green roofs reduced heat gain by 37% and 31%, respectively, confirming the role of material selection in influencing UHI mitigation effectiveness.

[36] expanded on this by analyzing the thermal performance of roof types at the city scale. Their findings showed that cool roofs are more effective at reducing nighttime temperatures and lowering universal thermal climate index (UTCI) values than green roofs. Nevertheless, both approaches were effective in reducing the duration of extreme heat stress conditions.

[67] explored the impact of vegetation coverage and plant species in green roofs during a heatwave in Athens. Their results showed that 100% grass coverage achieved a mean temperature reduction of approximately 0.7°C, with localized drops exceeding 2°C, surpassing sedum coverage in cooling efficacy. The extent of vegetation coverage was shown to be critical to achieving optimal cooling performance.

Moreover, [68] emphasized the synergistic effect of combining extensive green roofs with urban vegetation like trees. Their research demonstrated that such integration significantly reduces indoor cooling demand, while offering co-benefits such as shading and enhanced evapotranspiration. Despite the progress in quantifying thermal benefits, research gaps persist in evaluating the long-term durability, maintenance requirements, and cost-effectiveness of green infrastructure solutions.

Thermal regulation strategies have been analyzed across various building typologies. [69] used the EnergyPlus software to simulate the thermal performance of residential buildings in Lokoja, Nigeria, over a 10-year climatic dataset. Their results showed a 29.45% reduction in solar gains and a 1.90% decrease in annual operative temperatures through the optimization of building orientation, glazing, and shading demonstrating the high impact of design interventions on passive cooling.

In the industrial sector, [70] analyzed the role of insulation and rooftop photovoltaic (PV) systems in reducing energy consumption in Mexican industrial buildings. For temperate climates, roof insulation emerged as the most effective strategy, while in warmer regions, a combination of cool roofing or insulation with PV systems yielded the best outcomes. The findings underscore the importance of climate-responsive design in enhancing thermal performance.

In Ghana, energy efficiency policies have focused on appliance performance. [71] examined the prevalence of low-efficiency air-conditioners, revealing that over 85% fell into the lowest energy rating category. Their projections showed that transitioning to higher-efficiency inverter air-conditioners could save 260 GWh annually by 2020, with potential savings rising to 1,770 GWh by 2030. These findings support the call for regulatory reforms and market transformation strategies aimed at improving appliance standards and reducing national energy demand.

While current research provides robust evidence, yet there is limited longitudinal data on the lifecycle performance and economic viability of emerging insulation materials such as nanocellulose aerogels. Additionally, experimental validation of simulation models in real-world, air-conditioned environments is lacking, particularly in tropical climates. Furthermore, urban-scale assessments of UHI mitigation often overlook the socio-economic factors that influence adoption and maintenance of thermal regulation strategies.

2.7 Integrating Green Roofs into Urban Energy Grids

Green roofs (GR) have proven potential to enhance building performance through thermal regulation and pollutant reduction. According to [20], GRs can reduce cooling loads by up to 70% and lower indoor

temperatures by as much as 15°C, significantly improving occupant comfort and reducing energy demand. Moreover, their capacity to absorb air pollutants (PM2.5, NO2, O3) and reduce urban noise levels highlights their multifunctional environmental value.

Beyond these environmental benefits, [72] emphasized the importance of factoring in urban morphology, such as building heights and spatial arrangements, when analyzing GR impacts on ecological and microclimatic conditions. Their findings suggest a gap in accounting for temporal vegetation dynamics and public perception in urban planning models.

[73] adopted a Water-Energy-Food-Ecosystem (WEFE) nexus approach, asserting that both traditional and multilayer GR systems contribute toward the UN Sustainable Development Goals (SDGs). However, implementation challenges remain. [74] identified key enabling factors, including standardization, policy incentives, reliable NBS service delivery, and educational campaigns, as essential to scaling up GR adoption.

Real-world applications further illuminate these insights. [75] analyzed case studies in Seattle and Manama, demonstrating the potential for GRs integrated with solar and wind systems to improve energy self-sufficiency, reduce carbon emissions, and support smart grid development. Solar integration, in particular, was found to meet up to 83% of building energy demand under subsidized programs, underscoring financial incentives as critical adoption drivers.

Studies on renewable integration pinpoint the importance of combining energy efficiency measures with renewable generation for urban sustainability. [76] modeled Iran's electricity sector under renewable energy scenarios. Their analysis revealed that utilizing just 30% of the nation's solar and wind potential could reduce fossil fuel consumption by 82.97 MtOe and cut emissions by 221.54 MtCO2e by 2035. This reflects a compelling case for integrated approaches that merge renewables with passive strategies like green roofing.

A complementary insights from [77] compared Singapore's tech-based solar strategies with India's decentralized, cost-sensitive deployment model. Both cases emphasize how tailored approaches to renewable integration, in line with national contexts, can effectively support SDG 7 goals. In a broader analysis, [78] examined the interplay between renewable energy, digital economy, and energy intensity across 33 high-emission nations. They found that renewable energy plays the most significant role in reducing energy intensity, particularly in high-income countries, although digital technologies may inadvertently increase energy disparities.

These studies highlight a significant research gap: while the energy benefits of GR-solar hybrids are increasingly recognized, there remains a paucity of quantitative models that integrate GR thermal performance into national-scale energy planning and smart grid simulations.

Policy frameworks are central to unlocking the full potential of GRs in urban energy grids. [79] proposed a prioritization model for GR installation based on urban heat intensity, green space availability, and

retrofit potential. Their results suggest that synergistic interventions combining GRs with energy infrastructure offer optimal outcomes.

[80] examined GR policy development in China, identifying 23 policies across three implementation stages: pilot, progressive, and widespread application. These were categorized into mandatory, incentive-based, and assistance frameworks. Their study calls for context-specific adaptation, emphasizing the importance of economic development and urban structure in shaping effective GR policies.

A study by [81] took a spatial policy analysis approach using ArcGIS Pro and word frequency analytics. They found considerable regional disparities in GR policy distribution, a lack of diverse incentive types, and an underdeveloped rating system compared to green building initiatives. This indicates a pressing need to harmonize policy design and improve benchmarking systems for GR integration with energy goals.

2.8 Barriers to Green Roof Implementation: Socioeconomic and Technical Challenges

Green roofs also referred to as vegetated or living roofs have gained increasing attention as a viable nature-based solution for addressing the multifaceted challenges of urban climate change. In the context of rapidly urbanizing environments characterized by elevated surface temperatures, increased greenhouse gas concentrations, and declining air quality, green roofs provide a multifaceted strategy. Notably, they offer the dual advantage of carbon sequestration and energy efficiency. By capturing atmospheric carbon dioxide (CO₂) through vegetation and reducing building energy demands for thermal regulation, green roofs serve as both a carbon sink and a mechanism for mitigating indirect emissions associated with energy consumption.

The imperative to address global climate change remains urgent, especially given the central role of CO₂ as a long-lived greenhouse gas predominantly released through fossil fuel combustion. As highlighted by [82] and [83], the persistent rise in atmospheric CO₂ concentrations constitutes a critical environmental concern, intensifying the greenhouse effect and driving global temperature increases. Within this framework, green roofs emerge as a practical intervention with climate-resilient benefits.

Vegetation incorporated into green roof systems contributes to carbon mitigation through photosynthesis, whereby CO₂ is absorbed and stored in plant biomass and soil substrates [49, 84]. In parallel, the thermal insulation properties of green roofs help to reduce the need for artificial heating and cooling, thus decreasing building energy consumption and the associated carbon emissions [20]. This synergy between direct carbon sequestration and energy conservation reflects the strategic value of green roofs in urban carbon governance.

However, despite the promising environmental contributions of green roofs, their adoption remains constrained by a series of socioeconomic and technical barriers. Economically, the high upfront costs of installation constitute a significant impediment, particularly for private homeowners and small-scale developers. Although green roofs demonstrate superior durability estimated to outlast conventional roofs by a factor of three the initial financial outlay remains prohibitive in the absence of supportive fiscal policies [85].

In addition to cost-related challenges, limited public awareness and stakeholder skepticism continue to hinder adoption [86]. Moreover, the absence of robust policy frameworks and targeted incentives further exacerbates implementation gaps. Even in technologically advanced cities, uptake remains low when supportive regulatory structures are missing.

An often-overlooked consideration is the environmental equity dimension. In low-income urban neighborhoods, green roof adoption is particularly limited due to inadequate public investment and persistent disparities in access to sustainable infrastructure. This inequity contributes to heightened exposure to urban heat and air pollution, thereby reinforcing patterns of climate injustice [87].

From a technical standpoint, the successful deployment of green roofs necessitates careful attention to issues such as load-bearing capacity, drainage systems, waterproofing, and structural compatibility. [88] contend that retrofitting older buildings may, in some cases, be more cost-effective than integrating green roofs into new constructions. However, variations in local climatic conditions, plant species selection, and maintenance practices can significantly affect performance outcomes.

A further complication arises from the lack of standardized guidelines and performance metrics across regions. In areas subject to extreme weather conditions such as heavy rainfall or prolonged drought this absence of harmonized design codes introduces uncertainty for engineers and developers. Consequently, these technical ambiguities limit the scalability of green roofs and restrict their integration into mainstream urban planning strategies.

Methods

This study employed a systematic literature review approach, designed in alignment with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, to explore the dual role of green roofs in carbon sequestration and energy efficiency within the context of sustainable urban development. The methodology was structured to ensure transparency, reproducibility, and academic rigor, covering a comprehensive range of empirical and theoretical studies.

The literature search was conducted between April and May 2025 using five major databases known for high-impact publications: Scopus, Google Scholar, ScienceDirect, JSTOR, and MDPI. These platforms were selected for their multidisciplinary coverage and relevance to the studies.

To ensure broad capture of pertinent research, Boolean operators were employed with combinations of the following keywords:

- “green roofs” AND “carbon sequestration”
- “green roofs” AND “energy efficiency”
- “urban sustainability” AND “thermal insulation”
- “green infrastructure” AND “CO₂ mitigation” AND “building performance”

Searches were limited to peer-reviewed journal articles, published between 2009 and 2025, and written in English.

Articles were included based on the following criteria:

- Direct relevance to green roofs and their contribution to carbon sequestration and/or energy performance,
- Empirical case studies, modeling simulations, or theoretical frameworks,
- Urban or metropolitan application of green roof technologies.

Exclusion criteria ruled out:

- Non-peer-reviewed sources, editorials, and opinion pieces,
- Studies not focused on green roofs or lacking environmental/energy performance metrics,
- Non-English or inaccessible full-text articles.

An initial pool of approximately 3,000 articles was retrieved. After duplicate removal, 1,100 articles remained for title and abstract screening. The screening was independently conducted by two reviewers, with disagreements resolved through discussion.

Following this, 300 full-text articles were assessed for eligibility. Based on thematic alignment and methodological rigor, a final sample of 80 peer-reviewed articles was selected for in-depth analysis. The PRISMA diagram (Fig. 1) illustrates the selection process.

For each included article, data were extracted using a structured template capturing author(s), publication year, and geographic context, green roof characteristics, and vegetation types, carbon sequestration metrics and energy performance indicators, and methodological approaches (e.g., field measurements, simulations, lifecycle analysis). Thematic analysis was employed to identify commonalities and divergences in findings, categorizing the literature into two central themes: (1) carbon sequestration mechanisms; and (2) energy-saving performance of green roofs. This review is limited by its exclusion of grey literature, language restrictions, and potential database bias. The reliance on citation rankings may also underrepresent emerging but under-cited works.

Source: Authors’ Fieldwork, 2025.

Findings and Discussion

The reviewed studies reveal a coherent body of evidence demonstrating that green roofs contribute meaningfully to urban sustainability through two primary mechanisms: carbon sequestration and energy efficiency enhancement. These mechanisms emerge repeatedly in empirical measurements, modelling exercises, and long-term observational studies, underscoring the multifunctional value of vegetated roof systems in contemporary urban environmental management.

4.1 Carbon Sequestration Performance

Across the empirical literature, vegetation on green roofs consistently functions as a modest but reliable carbon sink. Species-specific studies show substantial variation in sequestration potential: *Sedum acre*, *Frankenia thymifolia*, and *Vinca major* exhibit annual atmospheric CO₂ absorption rates of 0.14, 2.07, and 0.61 kg/m² respectively [6]. Importantly, these direct uptake values are complemented by significant indirect emission reductions derived from improved building thermoregulation, with annual reductions ranging from 23.44 to 28.16 kg/m² due to decreased energy consumption [6]. Such findings confirm the dual role of vegetation in capturing carbon and reducing energy-related emissions.

The substrate also plays a central role in carbon storage. Although typically viewed as structural support, soil acts as an active carbon reservoir. Research on soil organic carbon dynamics suggests that stable long-term storage depends heavily on microbial processes, particularly the activity of arbuscular mycorrhizal fungi and melanising endophytic fungi, which promote the transformation of labile carbon into more persistent pools [43, 44]. [41] further contest the assumption that soil carbon is inherently unstable, arguing instead that microbial transformation pathways significantly enhance carbon permanence, an insight that has clear implications for green roof substrate design.

The literature comparing green roof types highlights that intensive systems outperform extensive ones in total sequestration capacity due to deeper substrates and higher biomass accumulation [47, 48]. Carbon payback analyses estimate that extensive roofs require between 6.4 and 15.9 years to offset embodied emissions, whereas intensive systems achieve shorter payback periods [47]. Long-term flux monitoring reinforces this pattern. [49] report annual total CO₂ reductions of 4,355.6 g/m² on an intensive roof, with only 46.6 g/m² attributable to direct uptake, while 4,309 g/m² derived from energy-related indirect reductions. This disparity highlights the predominance of indirect pathways in determining the overall climate value of green roofs.

Seasonal dynamics further influence sequestration. Studies show that direct uptake peaks in autumn, while indirect reductions are greatest in summer due to higher cooling loads [49]. Broader ecological work reinforces the importance of seasonality, with significant variations in gross ecosystem productivity (GEP) and ecosystem respiration (RE) shaping net carbon exchange [51, 52]. Yet few green roof studies explicitly quantify these seasonal physiological responses, creating a gap in current understanding.

Methodological inconsistencies also persist. Remote sensing approaches accurately capture above-ground biomass variation [45], but underestimate below-ground carbon, whereas field-based dry-weight assessments capture root contributions but lack spatial reach [46]. A combined methodological approach remains rare but necessary for comprehensive carbon accounting.

4.2 Energy Efficiency and Thermal Regulation

A second major theme across the reviewed literature concerns the thermal performance of green roofs and their role in reducing building energy demand. Evidence consistently demonstrates that green roofs moderate temperature extremes through evapotranspiration, shading, and increased insulation [20, 22]. Cooling load reductions of up to 70% and indoor temperature decreases of as much as 15°C have been documented, particularly in hot climates where green roofs alleviate peak heat stress [20].

Comparative analyses indicate that cool roofs reduce heat gain more efficiently during peak periods, yet green roofs provide broader multifunctional benefits [66]. Grass-dominated systems have been shown to outperform sedum-based ones during heatwaves, achieving mean temperature reductions of about 0.7°C and localized drops of over 2°C [67]. The significance of vegetation type is further underscored by [23], who note that plant selection and climatic alignment govern energy performance outcomes.

City-scale evaluations also show that green roofs reduce nighttime temperatures and improve thermal comfort, contributing to urban heat island mitigation [36]. Modelling studies suggest that these benefits persist under future climate scenarios, with thermal performance improving as heat intensifies [8]. The combination of green roofs with adjacent vegetation, such as trees, has been demonstrated to produce synergistic cooling effects and further reduce cooling demand [68].

Despite strong evidence for thermal benefits, several knowledge gaps remain. Few studies track long-term thermal performance as vegetation matures, a notable limitation given observed degradation or densification of plant cover over time [34]. Furthermore, while simulation models like EnergyPlus demonstrate strong predictive capacity [69], empirical validation in real-world tropical and subtropical environments remains limited.

4.3 Broader Sustainability Implications

Taken together, the reviewed evidence situates green roofs as multifunctional infrastructures capable of advancing multiple sustainability objectives. Their dual pathways of carbon mitigation direct sequestration and reduced energy demand which align with city-level climate frameworks and global decarbonization targets [55, 57]. Recent policy research also indicates that green-oriented technologies influence broader environmental governance systems, including carbon emission trading, green credit policies, and urban green innovation [58, 59, 61].

However, the literature also highlights systemic constraints. Implementation barriers which are high upfront costs, limited awareness, and inadequate policy incentives that continues to inhibit widespread

adoption [16, 85]. Structural and climatic challenges further complicate retrofit applications [88], while uneven distribution of green infrastructure amplifies social inequities in climate exposure [87].

In sum, the reviewed findings affirm that green roofs meaningfully enhance urban sustainability through their interconnected ecological and energy functions. Yet, fully realizing their potential requires methodological refinement, long-term performance monitoring, context-responsive policy frameworks, and equitable urban planning strategies.

Recommendations and Conclusion

The study establishes that green roofs deliver significant environmental benefits, particularly through carbon sequestration and improved energy efficiency, yet several constraints limit their widespread adoption. To maximize their potential, the study proposes targeted policy, technical, financial, and social interventions.

First, stronger regulatory frameworks are essential. Mandating green roofs in new public or commercial buildings, supported by clear performance standards, would accelerate adoption. Complementary economic incentives like tax rebates, grants, low-interest loans, and integration into carbon credit markets can reduce high upfront costs, especially for intensive systems with higher ecological returns.

Standardized performance metrics are needed to unify carbon accounting and thermal efficiency assessments. Such benchmarks would improve comparability across cities and guide design choices. Additionally, the study calls for enhanced research into substrate composition, soil carbon stability, and microbial contributions to long-term carbon storage, areas that remain underexplored yet central to sequestration dynamics.

Climate-responsive plant selection should be prioritized, as vegetation type strongly influences cooling and carbon uptake. Similarly, integrating green roofs into wider urban green infrastructure networks can amplify benefits such as stormwater control, biodiversity enhancement, and urban heat mitigation.

Awareness campaigns and professional training will help overcome skepticism and improve implementation quality. To ensure fairness, the study recommends prioritizing installations in low-income neighbourhoods that face disproportionate heat and pollution exposure.

In conclusion, green roofs are effective tools for enhancing urban sustainability by reducing carbon emissions, improving building energy performance, and moderating microclimates. Their long-term success depends on coordinated actions among policymakers, researchers, planners, and private stakeholders. When supported by robust incentives, rigorous scientific research, and equitable planning strategies, green roofs can evolve from isolated architectural features into vital components of climate-resilient, energy-efficient, and ecologically responsive urban systems.

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Figures

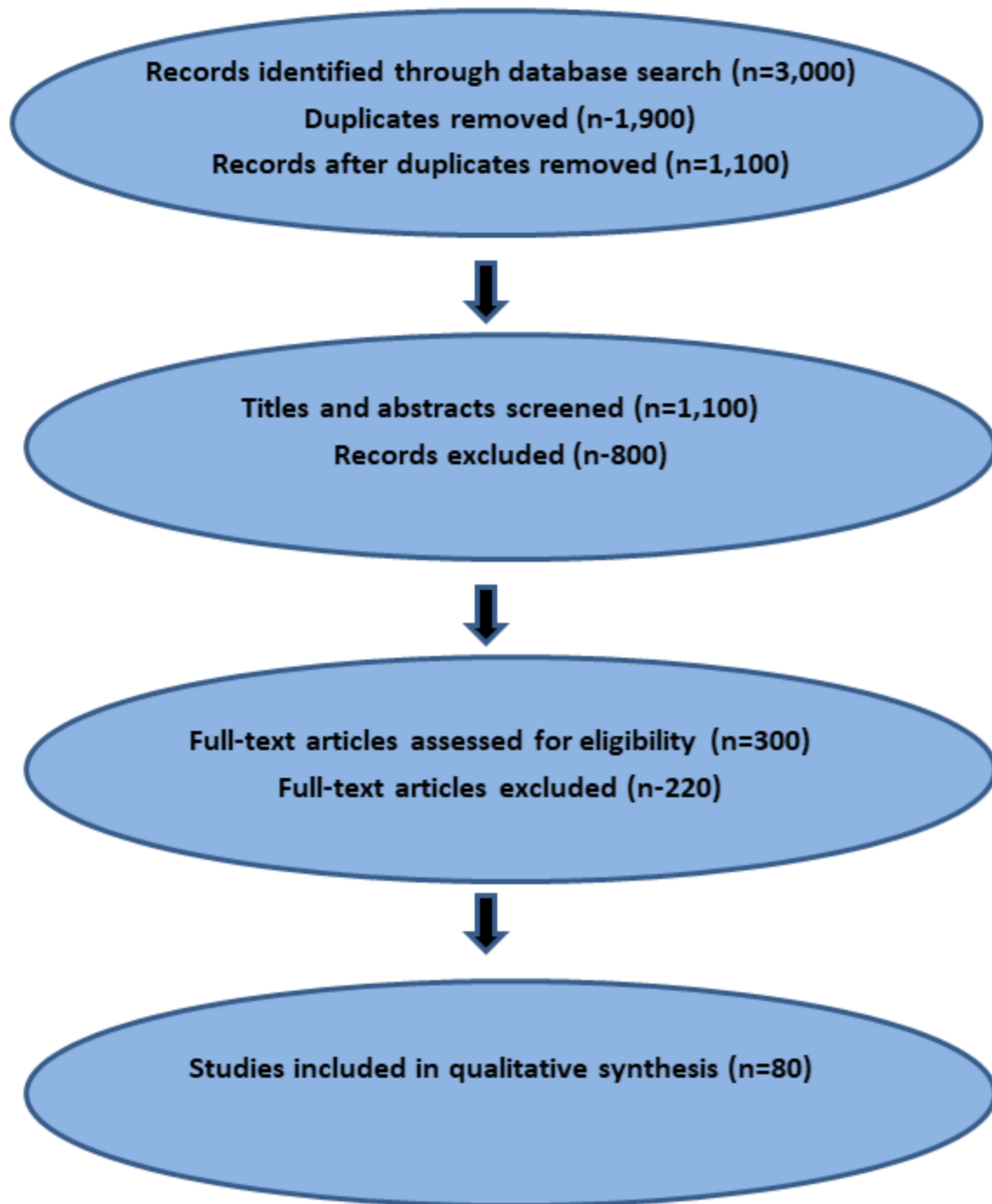


Figure 1

PRISMA Flow Chart

Source: Authors' Fieldwork, 2025.