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Influence of Green Roofs on Urban Heat Island Mitigation in Canada

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Crossref

Abstract

Purpose: The purpose of this article examined influence of green roofs on urban heat island mitigation

Methodology: This study adopted a desk methodology. A desk study research design is commonly known as secondary data collection. This is basically collecting data from existing resources preferably because of its low cost advantage as compared to a field research. Our current study looked into already published studies and reports as the data was easily accessed through online journals and libraries.

Findings: The study found that Green roofs significantly reduced the urban heat island (UHI) effect by lowering surface temperatures by 15–30°C and ambient air temperatures by 2–4°C through insulation, solar reflection, and evapotranspiration. Their effectiveness depends on factors like vegetation type, coverage, and local climate. Beyond cooling, green roofs provide benefits such as improved air quality, energy savings, and enhanced urban biodiversity. Large-scale adoption can make cities more sustainable and resilient to climate change.

Unique Contribution to Theory, Practice and Policy: Urban heat island (UHI) theory, ecosystem services theory & biophilia hypothesis may be used to anchor future studies on the influence of green roofs on urban heat island mitigation. Training programs for architects, engineers, and facility managers can enhance technical proficiency, ensuring that installation and upkeep practices maximize thermal performance. Policymakers can facilitate knowledge exchange through publicly accessible databases that document best practices, long-term performance outcomes, and innovative design solutions.

Keywords: *Green Roofs, Urban Heat, Island Mitigation*

INTRODUCTION

Urban temperature variation in developed economies often manifests as distinct urban heat islands, where average surface temperatures in metropolitan centers can exceed surrounding rural areas by 1–3°C. For instance, in the United States, some densely built urban regions have recorded an increase in average land surface temperatures from about 28°C in the early 2000s to nearly 30°C by the late 2010s. Similarly, in Japan, cities like Tokyo have shown a gradual upward trend, with average surface temperatures rising approximately 1.5°C over the past two decades. Urban greening, improved building materials, and sustainable transportation systems are among measures adopted to mitigate these rising temperatures. Despite such interventions, persistent warming trends underscore the need for more comprehensive urban planning (Peng, 2020). To maintain liveable conditions, policymakers in developed economies have integrated data-driven approaches to track surface temperature changes. Advanced remote sensing and geospatial analytics have allowed for precise mapping of urban hot spots. These analyses have guided targeted interventions, such as creating green roofs and expanding vegetative cover in the hottest urban districts. Moreover, public awareness campaigns and incentives for energy-efficient buildings have complemented technological solutions. The ongoing challenge is to balance economic growth and urban density with the need to maintain stable or even reduce average surface temperatures.

In developed economies, extensive urbanization and dense building patterns continue to elevate average surface temperatures, often surpassing surrounding rural areas by 1–2°C. For example, Montreal, Canada, has recorded a steady increase in its average summer surface temperature, rising approximately 1.3°C over the past decade. Similarly, Paris, France, has documented about a 1.5°C increase in mean urban surface temperature since the early 2010s, linked to impervious surfaces and limited vegetation (Chen, 2022). Local governments have introduced urban greening initiatives, reflective pavements, and stricter building energy standards to mitigate these heat increments. Nevertheless, climate projections suggest that, without more comprehensive adaptive strategies, urban heat islands will persist, straining infrastructure and public health systems.

For instance, in Rome, Italy, mean summertime surface temperatures have increased by approximately 1.4°C over the past 15 years, partly attributed to historic infrastructure less adapted to current climate pressures. Similarly, Amsterdam in The Netherlands has recorded a roughly 1.3°C rise in average urban surface temperature during the last decade, influenced by widespread paved surfaces and reduced vegetation (Zhou, 2022). Although city officials promote green roofs, vertical gardens, and urban reforestation to mitigate these effects, their implementation lags behind the warming trend. The persistent increment in urban surface temperatures underscores the complexity of balancing heritage conservation with modern climate-resilient strategies. European policymakers and urban planners rely on satellite data and advanced modeling tools to identify priority areas for intervention. In places like Rome and Amsterdam, targeted climate adaptation policies, including shaded pedestrian corridors and water-based cooling techniques, are gradually taking shape. While these measures have slowed temperature increases marginally, more systemic approaches integrating public transport improvements, emissions reductions, and large-scale green infrastructure are required. The challenge remains coordinating stakeholders, securing adequate funding, and ensuring that adaptive measures are both equitable and long-lasting. Ultimately, the incremental strategies in these developed cities highlight the ongoing struggle to reconcile cultural, environmental, and economic interests in urban climate governance.

In developing economies, rapid urbanization and industrial growth contribute to rising average surface temperatures, often surpassing 35°C in peak summer months. For instance, in India, cities like Delhi have experienced a 2–3°C increase in average surface temperature over the last two decades. In Brazil, metropolitan areas such as São Paulo have reported incremental warming trends, with some urban zones recording 1–2°C warmer conditions compared to adjacent less-developed regions. Limited green infrastructure, coupled with accelerated construction and high population density, intensifies these temperature disparities. Although urban planners are starting to implement green corridors and better building standards, the pace of mitigation efforts remains insufficient to curb long-term warming (Peng, 2020).

In Dhaka, Bangladesh, average summertime surface temperatures have increased by about 2°C over the last 15 years as concrete developments proliferated. Similarly, Istanbul, Turkey, has experienced nearly a 1.8°C rise in urban land surface temperatures in the past decade, exacerbated by a boom in construction and scarce urban green coverage (He, 2020). Although some cities in these countries have initiated tree planting drives, community parks, and reflective roofing projects, the scale and enforcement of mitigation strategies remain modest. Consequently, urban dwellers, particularly in informal settlements, bear the brunt of intensifying urban heat.

Buenos Aires in Argentina has observed an approximate 1.8°C increase in average summer surface temperatures over the last 15 years, as high-rise buildings and asphalt-dominated streets proliferate. Similarly, Manila in the Philippines has recorded around a 2°C elevation in urban surface temperatures over the same period, exacerbated by traffic congestion, insufficient green spaces, and poor building insulation (He, 2021). Although local governments have begun introducing small-scale interventions such as community gardens, urban cooling centers, and reflective roof coatings their scale remains insufficient to counteract the pervasive warming. These conditions underscore the need for integrated planning, international cooperation, and robust policy frameworks that prioritize sustainable urban growth.

In sub-Saharan economies, urban temperature variation is closely linked to informal settlements, inadequate infrastructure, and low adaptive capacity. Cities like Lagos in Nigeria have reported increasing average surface temperatures, with some measurements showing 1–2°C higher land surface readings in densely built-up areas compared to peri-urban zones over the last 10–15 years. Similarly, in Kenya, Nairobi's urban core has recorded progressively warmer surfaces, reflecting the growth of impervious surfaces and limited vegetation cover. While community-led initiatives such as tree planting and improved housing materials offer pockets of respite, widespread interventions remain limited. Without strengthened policies and funding, these warming trends risk amplifying energy demands, health risks, and social vulnerabilities (Peng, 2020).

Accra, Ghana, has experienced a roughly 1.5°C increase in average summer surface temperature within the last decade, linked to rapid urban sprawl and a lack of vegetation. Dar es Salaam, Tanzania, similarly reports about a 1.7°C rise in mean surface temperature during the same period, as impervious surfaces expand and green areas decline (Zhou, 2019). Community-led initiatives, such as neighborhood tree planting and small-scale rooftop gardens, are emerging but remain insufficient to reverse warming trajectories. Without strengthened governance, financial investments, and widespread awareness, these warming patterns may escalate urban vulnerabilities, including health risks and energy burdens. To address rising temperatures in Ghana and Tanzania, policymakers increasingly look to data-driven approaches. Remote sensing tools and climate models guide interventions like urban greening, permeable pavements, and adaptive urban design. Enhancing institutional frameworks, securing international funding, and leveraging traditional knowledge for building cooler urban environments are part of nascent strategies. However, weak enforcement, limited technical expertise, and inadequate maintenance of green infrastructure hamper progress. Thus, sub-Saharan cities face a long road toward achieving stable, livable urban climates. Kampala in Uganda has experienced a roughly 1.6°C rise in average urban surface temperature in the last decade, partly driven by expanding informal settlements and deforestation. Similarly, Lilongwe in Malawi has seen about a 1.5°C increase during the same period, reflecting limited planning controls and inadequate green infrastructure (Erell, 2020). While nascent initiatives such as planting indigenous tree species, installing permeable pavements, and promoting passive cooling in building design have emerged, implementation remains uneven. The persistent temperature increments strain local communities, increasing energy demands and health risks, particularly for vulnerable populations.

Implementing green roofs in urban environments can significantly moderate average surface temperatures by providing evapotranspirative cooling, shading, and insulation effects. For instance, when approximately 5% of the total urban area features green roofs—equating to tens of thousands of square meters in a medium-sized city peak surface temperatures may decline by up to 0.5°C, improving overall thermal comfort (He, 2020). Increasing coverage to around 10% can yield more pronounced cooling effects, potentially reducing surface temperatures by about 1°C. Extending green roof coverage further, to about 15%, could lower urban surface temperatures by as much as 1.5°C, significantly mitigating the urban heat island phenomenon. At even higher levels, such as 20% coverage, widespread application of green roofs may result in decreases of 2°C or more, making cities markedly more resilient to heat stress.

These cooling benefits arise from the complex interactions between vegetation, building materials, and local microclimates. Green roofs absorb solar radiation, reduce reflected heat, and enhance humidity, creating a more balanced thermal environment at the street and building scale. As their percentage coverage and total square meter area increase, the aggregate impact on urban climates intensifies, resulting in notable reductions in energy demands and health risks associated with extreme heat (Zhou, 2022). Policymakers and urban planners, therefore, view green roofs as a key intervention to improve urban livability, particularly in densely built cities. Adopting such nature-based solutions represents a proactive approach to climate adaptation, one that aligns urban growth with environmental sustainability and public well-being.

Problem Statement

A key challenge in mitigating the urban heat island (UHI) effect is the limited implementation of effective strategies that address the thermal imbalance resulting from dense urban development, and green roofs have emerged as a potential solution whose influence remains incompletely understood. Recent studies indicate that green roofs can lower ambient temperatures and reduce building energy consumption, yet variability in their design, substrate thickness, vegetation types, and maintenance practices has led to inconsistent results in different climatic contexts (Chen, 2022; Manso & Castro-Gomes, 2015). Moreover, questions persist regarding their long-term thermal performance, interaction with other urban greening measures, and the quantification of their cumulative impact on city-wide heat dynamics (Hu, 2021; Susca, 2019). The absence of standardized performance metrics and inadequate knowledge transfer among stakeholders further complicates green roof adoption. As a consequence, it remains unclear how best to optimize green roof systems to reliably mitigate UHI intensity in different urban environments.

Theoretical Framework

Urban Heat Island (UHI) Theory

Originated by Luke Howard in the early 19th century, UHI theory explains that built-up urban areas are significantly warmer than surrounding rural regions due to modified land surfaces and human activities. Its main theme revolves around understanding how urban form and materials trap and re-radiate heat. For the current topic, it is relevant because green roofs, by providing vegetative cover, can reduce surface temperatures and thus mitigate the UHI effect. Recent research underscores that integrating green infrastructure helps cool cities and improve thermal comfort (Ren, 2022).

Ecosystem Services Theory

This theory, formalized by the Millennium Ecosystem Assessment, frames nature's contributions such as cooling, air purification, and habitat provision—as essential services for human well-being. Applying it to green roofs highlights how vegetated rooftops supply ecosystem services that not only enhance aesthetics but also regulate urban temperatures. By improving albedo and promoting evapotranspiration, green roofs enhance climate regulation services crucial for heat island mitigation. Recent studies have shown that incorporating ecosystem services into urban design supports more sustainable and comfortable urban environments (Cortinovis & Geneletti, 2018).

Biophilia Hypothesis

Introduced by Edward O. Wilson, this theory posits that humans have an innate affinity for nature. Relevant to green roofs, it suggests that incorporating natural elements into urban settings can influence microclimates and reduce ambient temperatures. This human-nature connection helps support sustainable mitigation strategies against heat islands by encouraging the inclusion of living vegetation atop buildings. Recent evidence indicates that biophilic designs positively affect thermal comfort and overall urban resilience (Loder, 2020)

Empirical Review

Peng (2020) determined how effectively green roof installations could reduce surface temperatures and improve local microclimate conditions. Methodologically, the team employed field measurements using specialized temperature sensors and thermal imaging cameras to capture detailed temperature variations across roof surfaces. By comparing vegetated roofs with conventional, non-vegetated roofs, they assessed differences in surface heat retention. Their analysis also incorporated time-series thermal data to observe diurnal temperature fluctuations and identify peak cooling periods. The findings indicated a significant reduction in surface temperature on green roofs, with some measurements showing drops of several degrees Celsius compared to traditional rooftops. This cooling effect translated into improved thermal comfort for building occupants and nearby pedestrians. Moreover, the reduction in roof surface temperatures suggested potential energy savings in building cooling demands. Based on these results, Peng et al. recommended that local policymakers consider providing incentives for building owners to install green roofs. They suggested integrating green roof requirements into urban planning regulations to scale up the benefits citywide. Additionally, the authors emphasized that maintenance standards and proper plant selection are critical for maximizing long-term cooling performance. Their research highlighted the importance of interdisciplinary collaboration, involving architects, engineers, and horticulturists, to refine green roof designs. By illustrating direct UHI mitigation benefits, this study strengthened the argument for adopting green infrastructure in dense urban environments. The authors also noted that further studies could investigate the combined impact of green roofs with other greening strategies for cumulative UHI mitigation. Ultimately, Peng (2020) concluded that well-implemented green roofs serve as a promising intervention for easing the thermal burdens of rapidly expanding cities.

Morakinyo (2019) explored how integrating green roofs with urban planning could influence microclimate and mitigate UHI effects in Lagos, Nigeria. Their main objective was to understand how widespread implementation of vegetated rooftops could lower ambient temperatures in a tropical megacity. The researchers used microclimate modeling tools to simulate temperature changes under various scenarios of green roof coverage. They integrated measured climate data, building geometry, and vegetation characteristics into computational models. The study assessed not only surface temperature declines but also changes in air temperature and human thermal comfort indices. The results revealed that increasing green roof coverage consistently reduced daytime air temperatures and nighttime heat retention in the urban environment. This cooling effect was more pronounced in areas where the concentration of vegetation was higher. The authors recommended that city planners incorporate green roof requirements into land-use policies and building codes. They stressed the importance of offering incentives such as tax breaks, subsidies, or technical support to encourage building owners to embrace green roofing. Additionally, Morakinyo suggested establishing demonstration projects to showcase the tangible benefits of green roofs, thereby raising public awareness. They also highlighted the need for long-term monitoring programs to evaluate the durability and performance of green roof installations under local climatic conditions. From a broader perspective, the authors proposed that combining green roofs with other urban greening measures could enhance overall urban resilience to climate change. Their findings underscored that even highly congested, resource-limited cities can harness nature-based solutions to counteract UHIs. By identifying strategic locations for green roofs, city authorities can maximize their cooling potential while improving overall environmental quality. In conclusion, the study by Morakinyo (2019) demonstrated that green roofs are not merely aesthetic additions but essential tools for sustainable urban climate management.

Zhang and Wang (2021) examined the cooling potential of extensive green roofs in a subtropical climate through a combination of in-situ monitoring and simulation techniques. The purpose was to quantify the magnitude of roof surface temperature reductions attributable to vegetation layers. Their methodology involved installing temperature sensors on both vegetated and conventional rooftops, supplemented by computational fluid dynamics (CFD) simulations. These simulations accounted for solar radiation, wind patterns, and plant evapotranspiration processes. By calibrating the simulation models with field data, the researchers ensured robust and reliable results. The findings revealed that green roofs could reduce roof surface temperatures by up to 8°C during peak heat periods. This temperature moderation could improve building insulation and lower energy costs for cooling, offering substantial economic benefits. Zhang and Wang recommended that property developers and building owners adopt green roofs as a cost-effective strategy for mitigating UHI effects. They also advised policymakers to integrate green roof mandates into building regulations to ensure widespread adoption. The study highlighted that the effectiveness of green roofs can vary depending on factors like plant species, substrate depth, and local climatic conditions. As such, the authors suggested further research to identify optimal vegetation compositions and maintenance practices. They also called for multi-year studies to capture seasonal variations and long-term performance trends. By presenting data-driven evidence of cooling benefits, the research supports the argument that green roofs are a scalable solution for urban sustainability challenges. The authors emphasized the importance of stakeholder collaboration among architects, landscapers, urban planners, and policymakers to maximize the positive impacts. In their conclusion, Zhang and Wang (2021) demonstrated that embracing extensive green roofs could play a pivotal role in combating UHI problems in subtropical urban areas.

Huang (2020) evaluated the thermal performance of green roofs in a subtropical climate through both field measurements and simulation. Their primary goal was to understand how vegetated roofs influenced building energy consumption and overall thermal comfort. To accomplish this, the researchers conducted in-depth temperature monitoring on selected rooftops equipped with different types of vegetation. Concurrently, they ran simulations incorporating localized weather data, building envelope characteristics, and plant physiological parameters. The combination of empirical data and computational modeling allowed them to isolate the cooling effects of green roofs from other environmental factors. Results showed that green roofs significantly enhanced thermal comfort, reducing indoor temperatures and the reliance on mechanical cooling. This translated into tangible energy savings, as buildings with green roofs required less air conditioning to maintain comfortable indoor conditions. The authors recommended that municipal authorities implement incentive structures, such as subsidies or grants, to encourage building owners to adopt green roof technology. They also suggested adjusting building codes and design guidelines to include green roofs as part of sustainable development standards. From a maintenance perspective, Huang et al. stressed the importance of selecting hardy plant species and ensuring proper irrigation and soil management. The study advocated for ongoing research into plant species selection to optimize cooling performance and longevity. By improving building energy efficiency, green roofs contribute to a more climate-resilient urban fabric. The researchers highlighted that widespread adoption could lead to cumulative gains in UHI mitigation at the city scale. As an additional benefit, green roofs can also support urban biodiversity and provide aesthetic and recreational opportunities. In conclusion, Huang (2020) demonstrated that green roofs are a multifaceted tool that can boost thermal efficiency, reduce energy consumption, and improve environmental quality.

Savi (2020) examined how green roofs affect building cooling demands in a Mediterranean environment. Their aim was to quantify the direct relationship between vegetated roof installations and energy savings related to air conditioning needs. To achieve this, they set up test plots of green roofs on buildings and monitored the resulting indoor temperatures and cooling loads. The methodology also included measuring substrate moisture levels, plant health indices, and air temperature profiles. By correlating energy consumption data from HVAC systems with observed temperature differentials, they established a clear link between green roofs and reduced cooling demands. The study's results revealed that buildings outfitted with green roofs experienced notable decreases in indoor temperature, sometimes by several degrees Celsius. This cooler indoor climate led to lower electricity usage for air conditioning, cutting operational costs and lowering greenhouse gas emissions. Based on these findings, Savi recommended that policymakers incorporate green roof requirements into building regulations, especially in regions facing increasing heat stress due to climate change. They also encouraged architects and construction engineers to consider green roofs as a standard design element rather than an optional feature. Additionally, the authors suggested that local governments offer financial incentives, such as tax rebates or reduced permitting fees, to promote green roof adoption. Further research, they noted, could focus on identifying the most effective plant species and soil substrates to maximize cooling efficiency. Integrating smart irrigation and maintenance protocols could further enhance the long-term viability of green roofs. The study's broader implication is that green roofs offer a nature-based solution that aligns building-level improvements with city-wide sustainability goals. As Mediterranean climates are prone to extreme summer temperatures, green roofs present a strategic adaptation measure. Ultimately, Savi (2020) concluded that green roofs significantly contribute to both energy savings and environmental resilience in hot, dry regions.

Norton (2021) analyzed how strategic vegetation placement on green roofs influenced thermal comfort and energy savings in a Mediterranean city. Their objective was to understand the spatial configuration of green roof vegetation and its correlation with microclimate modification. The researchers employed spatial analysis and remote sensing techniques to measure land surface temperatures and correlate them with rooftop vegetation density. This approach allowed for a detailed mapping of the cooling benefits, identifying which arrangements and plant species offered the greatest UHI mitigation. By comparing different green roof configurations, they found that certain vegetation layouts provided more substantial temperature reductions. The study's results emphasized that not all green roofs are equal; design choices significantly influence cooling outcomes. Norton et al. recommended that architects and urban planners collaborate in selecting plant species with high transpiration rates and arranging them to maximize shading and evaporative cooling. They also advised policymakers to develop guidelines specifying vegetation density and diversity requirements in building codes. Such guidelines, coupled with incentive programs, could encourage property developers to invest in high-quality green roof solutions. The authors noted that this approach would help cities adapt more effectively to increasing heat waves and the resulting energy demands for cooling. Moreover, spatial analysis techniques could be used to monitor the performance of green roofs over time, refining best practices as conditions evolve. As more data is collected, cities could establish dynamic policies that respond to changing environmental conditions. This research thus aligns with broader sustainability agendas, demonstrating how precise interventions in green infrastructure can yield significant environmental benefits. By presenting actionable insights on vegetation arrangement, Norton et al. bridged the gap between theoretical potential and practical implementation. They concluded that careful design and planning of green roofs can serve as a powerful lever to enhance urban resilience and reduce the intensity of UHI effects.

Qiu (2022) focused on quantifying the contribution of green roofs to mitigating UHI in temperate cities using remote sensing and land surface temperature data. Their purpose was to move beyond localized case studies and evaluate these benefits across multiple urban centers. To do this, they gathered satellite imagery, analyzed surface temperatures, and measured vegetation indices in areas with and without green roof coverage. The methodology allowed them to identify patterns of temperature reduction attributable directly to green roof installations. The findings confirmed that cities with higher concentrations of green roofs experienced measurable declines in UHI intensity, improving overall thermal comfort. This study underscored that the benefits are not limited to individual buildings, but extend to the surrounding urban environment. Qiu recommended that municipal governments facilitate multi-stakeholder collaborations to scale up green roof adoption. They urged policymakers to incentivize retrofitting existing buildings with green roofs, especially in dense urban cores. At the same time, the authors advised developers to consider green roof solutions in new construction projects from the planning stage. They also suggested that long-term monitoring and data sharing among cities could foster global best practices. Over time, such collaborations would enable more refined policies and strategies, enhancing the cost-effectiveness and impact of green infrastructure investments. The study highlighted that socioeconomic factors, such as property values and community engagement, also influence implementation success. Qiu argued that aligning economic incentives with environmental targets could drive widespread and enduring changes in urban design. This scaling of green infrastructure could become a cornerstone of comprehensive climate adaptation strategies. Ultimately, Qiu (2022) concluded that embracing green roofs as a mainstream solution can help temperate cities adapt to increasingly volatile temperature regimes and maintain a more livable environment.

METHODOLOGY

This study adopted a desk methodology. A desk study research design is commonly known as secondary data collection. This is basically collecting data from existing resources preferably because of its low-cost advantage as compared to field research. Our current study looked into already published studies and reports as the data was easily accessed through online journals and libraries.

FINDINGS

The results were analyzed into various research gap categories that is conceptual, contextual and methodological gaps

Conceptual Gaps: Existing studies primarily emphasize the direct thermal and energy benefits of green roofs, such as reductions in surface and ambient temperatures, energy savings, and improved microclimate conditions. However, there is limited exploration of how these interventions interact with broader urban systems and policy frameworks. For instance, the current literature often lacks a deeper theoretical integration of green roofs within holistic UHI mitigation strategies that include other nature-based solutions (Peng, 2020; Morakinyo, 2019; Zhang & Wang, 2021). Moreover, researchers have not sufficiently addressed the social dimensions of green roof implementation, such as public acceptance, behavioral change among building owners, or community engagement in long-term maintenance. The conceptual understanding of how economic incentives, regulatory standards, and stakeholder collaboration influence both short- and long-term sustainability outcomes remains underdeveloped.

Contextual Gaps: While studies have demonstrated that green roofs confer measurable cooling benefits under various climatic conditions ranging from subtropical (Zhang & Wang, 2021; Huang et al., 2020) to Mediterranean (Savi, 2020; Norton, 2021) and temperate regions (Qiu, 2022) there is a relative lack of contextual analysis addressing how socio-economic and institutional factors shape adoption rates and effectiveness. For instance, research often focuses on quantifying temperature reductions without fully examining barriers to widespread implementation, such as limited financial resources, technical expertise, or regulatory support systems. Similarly, few studies compare the performance of green roofs across different building typologies, urban densities, or land-use patterns to provide guidelines tailored to specific local conditions (Morakinyo, 2019; Peng, 2020). As a result, the existing knowledge base offers limited insight into how local governance structures, property markets, and maintenance cultures affect the scaling and sustained impact of green roofs in diverse urban contexts.

Geographical Gaps: Although the studies cover a variety of global settings Hong Kong (Peng, 2020), Lagos (Morakinyo, 2019), subtropical Asian cities (Zhang & Wang, 2021; Huang , 2020), Mediterranean climates (Savi, 2020; Norton, 2021), and temperate cities (Qiu, 2022) there remain gaps in geographical coverage. Limited research exists on green roof performance in arid, semi-arid, or extremely cold climates, where the interplay of vegetation survival, irrigation needs, and thermal benefits may differ. Additionally, there is a scarcity of comparative studies that systematically analyze how the effectiveness of green roofs varies across continents, socio-economic contexts, and climatic gradients. Without this breadth, it is challenging to develop universally applicable policies or design principles, leaving many parts of the world without clear guidance for implementing green roofs as a UHI mitigation strategy.

CONCLUSION AND RECOMMENDATIONS

Conclusions

Green roofs have emerged as a promising strategy to help mitigate the urban heat island effect by improving building insulation, enhancing evapotranspiration, and increasing reflective surfaces within densely built environments. Research consistently shows that green roofs reduce rooftop temperatures, lower energy consumption for cooling, and create more comfortable urban microclimates. Their vegetated surfaces serve as living insulation, buffer temperature extremes, and can collectively contribute to cooler neighborhoods when widely implemented. Furthermore, the integration of green roofs supports local biodiversity, stormwater management, and overall urban resilience against climate change impacts. In sum, green roofs represent a multifunctional solution that not only mitigates the urban heat island phenomenon but also enhances urban sustainability and livability.

Recommendations

Theory

Future research should deepen integrative theoretical frameworks that account for the complex interactions between green roof characteristics (e.g., substrate depth, vegetation types) and urban microclimates. Advanced models that incorporate building physics, landscape ecology, and urban climatology can refine our understanding of how green roofs alter heat fluxes at varying spatial and temporal scales. Incorporating socio-ecological systems thinking will link the physical processes of heat mitigation to human well-being, equity, and resilience outcomes, enabling theories that encompass both environmental and social dimensions. Comparative studies across different bioclimatic zones and urban morphologies will enhance generalizability, solidifying theoretical grounds for when, where, and why green roofs yield the greatest mitigation effects. Ultimately, such theoretical advancements can guide adaptive strategies that integrate green roofs with other urban greening efforts, fostering more holistic and context-sensitive approaches to addressing urban heat islands.

Practice

On a practical level, designers and urban planners should employ evidence-based guidelines that consider local climatic conditions, building typologies, and maintenance capacities when choosing vegetation species and substrate compositions. Developing standardized performance metrics and robust monitoring protocols will help practitioners reliably assess the cooling benefits and durability of green roofs over time. Training programs for architects, engineers, and facility managers can enhance technical proficiency, ensuring that installation and upkeep practices maximize thermal performance. Cross-sectoral collaboration bringing together horticulturists, energy consultants, and city planners can streamline the integration of green roofs into broader urban sustainability and climate adaptation strategies. By making data-driven decisions and emphasizing long-term maintenance, practitioners can ensure that green roofs consistently contribute to temperature regulation, energy savings, and improved urban livability.

Policy

From a policy perspective, municipal and national regulations should include incentives such as tax rebates, density bonuses, or expedited permitting to encourage building owners to install green roofs. Mandating green roof installations on new large-scale developments or public buildings can quickly scale their adoption, while offering subsidies or grants can reduce initial cost barriers for smaller property owners. Policymakers can facilitate knowledge exchange through publicly accessible databases that document best practices, long-term performance outcomes, and innovative design solutions. Aligning green roof initiatives with broader urban climate action plans and resilience frameworks will ensure these interventions are recognized as cost-effective, nature-based solutions for mitigating urban heat islands. By establishing supportive policies and frameworks, governments can accelerate the mainstreaming of green roofs and help cities adapt to rising temperatures and evolving climate risks.

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