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URBAN RESILIENCE THROUGH GREEN INFRASTRUCTURE: MITIGATING THE URBAN HEAT ISLAND (UHI) EFFECT

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Abstract
Rapid urbanization has intensified the Urban Heat Island (UHI) effect, leading to rising ambient temperatures, increased energy demand, and deteriorating thermal comfort in cities. This review explores the role of green infrastructure in addressing these challenges, emphasizing their effectiveness in mitigating urban heat island effect and in turn enhancing environmental sustainability and urban resilience. Green infrastructure involves incorporating strategies such as green roofs, rain gardens, parks and urban tree canopy. This approach has emerged as a viable strategy to mitigate UHI impacts while enhancing urban resilience. Green Infrastructure reduces surface and air temperatures, heat storage in urban materials, energy demand for cooling, nighttime heat retention thermal discomfort and health risk. Yet, challenges such as limited land availability, public awareness, competing urban development priorities, governance barriers, and maintenance costs hinder widespread adoption. Supportive policy frameworks, financial incentives and public engagement initiatives are vital in overcoming these challenges. It is imperative that policy makers, urban planners, stakeholders and other building professionals collaborate to ensure successful implementation of green infrastructure. This review is set to highlight the long-term environmental advantages of green infrastructure in ameliorating the urban heat island effect. It underscores the need for continuous research, technological innovation, and interdisciplinary cooperation to optimize these strategies for global adoption. Ultimately, integrating green infrastructure into the urban fabric can contribute to mitigating urban heat island effect contributing to urban resilience and environmental sustainability.

1. INTRODUCTION

Urban heat islands (UHI) are areas of concentrated heat that develop in cities thereby causing urban areas to experience higher temperatures than their rural surrounding due to human activities and the built environment.

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With the rapid increase in the rate of urbanization, green and blue spaces been replaced with concrete and glass structures urban heat island effect (J & Pradhan, 2025). This issue primarily stem from the increase in land and surface temperature resulting in elevated temperature in the urban environment is a critical issue that needs urgent attention. UHI are attributed to the anthropogenic activities which significantly alter the land and surface temperature of the urban area. These activities include extensive impermeable surfaces, high concentration of concrete structures, urban structures, limited green and blue spaces and human induced heat emissions (Bao et al., 2025). To mitigate the UHI effect, adopting resilient strategies such as green infrastructure is crucial. GI can alleviate temperature increase while improving thermal comfort. Green Infrastructure is a pragmatic solution for curbing Urban heat island effect.

GI strategies involves both natural and intentional greening – parks, urban forests, street trees and greenery, green roofs. gardens, wetlands (Balany et al., 2020). These strategies as well enhance ecosystem resilience by providing habitat for various species and mitigating the heat island effect (Lian et al., 2025). GI offers a practical and sustainable UHI mitigation approach. Recent studies have highlighted its effectiveness in reducing elevated urban temperatures and enhancing urban biodiversity. For instance, research indicates green infrastructure provide a significant cooling effects by reducing temperature by up to 6 degrees celsius (Ming et al., 2025). In addition, adoption of green infrastructure signifies a proactive stride toward fostering cities that effectively address the multifaceted challenges posed by climate change (Lopes et al., 2025).

In cities, GI strategies are not only beneficial for urban heat mitigation but also play role in air quality, which can help mitigate air pollution due to their ability to capture carbon emissions (Ai & Yan, 2024). Various studies have explored green infrastructure from different angles, highlighting its application in urban flood management, air pollution, environmental resilience, biodiversity advancement and climate resilience. One of the key advantages of GI strategy is that it delivers multiple co-benefits simultaneously, such as reducing urban heat island effects, managing stormwater and enhancing biodiversity.

The phenomenon of the urban heat island has emerged as a significant concern especially with the rapid growth of urbanization (Raghad Almashhour et al., 2024). Urbanization which is marked hard landscaping, concrete and carbon emitting structures, heat retaining structures, impervious surfaces which has significantly elevated air temperature in urban areas. Rather than the temperature being regulated by green bodies, their absence underscores the climbing urban temperatures. The effect of this challenge is further exacerbated by climate change, which increases the frequency and severity of heat waves, amplifies temperature extremes in built-up areas, and reduces the cooling capacity of natural systems (Joshi et al., 2024), (Zou et al., 2024). Consequently, there is an increasing acknowledgment of the need for sustainable and resilient strategies, with green infrastructure emerging as a prominent and viable approach.

As urbanization progresses, the extent of heat generation in cities continues to grow, leading to various heat-related challenges, including intensified urban heat island effects, heat waves, increased energy demand for cooling, reduced thermal comfort, and heightened risks to human health and comfort (Joshi et al., 2024). In response to these challenges, numerous nations and institutions have employed diverse sustainable measures and technological innovations, with green infrastructure gaining prominence as an effective and versatile solution to the urban heat island effect (Lian et al., 2025). Rather than relying solely on engineered solutions characteristic of grey infrastructure, green infrastructure integrates ecological and nature-inspired mechanisms aimed at promoting sustainable and resilient urban development (Herath, 2024). Green Infrastructure involves nature-based strategies and technologies that abate UHI effect. Examples of Geen Infrastructure includes bioswales, constructed wetlands, rain gardens, green roofs, street trees, and water bodies. Beyond addressing the urban heat island phenomenon, this strategy supports broader environmental objectives such as the enhancement of strengthened urban water management, greater biodiversity conservation, improved air quality, and expanded opportunities for outdoor recreation. Although the benefits of green infrastructure are well established, assessing its performance poses significant challenges, largely influenced by geographic conditions and socio-economic disparities (Liao & Hwan Yong Kim, 2024). Green infrastructure performance depends on an interplay of design quality, maintenance approaches, environmental context, and public involvement. Beyond addressing thermal regulation, its impacts also include economic, social, and ecological benefits, thus requiring comprehensive and multidimensional evaluation frameworks (Jones & Russo, 2024).

In addressing the effects of urbanization, green infrastructure have been proposed as effective strategies. GI is the incorporation of natural systems, such as wetlands, green roofs, rain gardens and street trees to help restore natural pattern in order to mitigate urban heat island effects. This paper reviews current research on green infrastructure underscoring their role in addressing UHI. The objective of this study is to examine the role and functionality of GI in urban thermal environment and mitigating urban heat island. Effective UHI management has become a critical issue in urban planning due to the pressures of urbanization. Conventional gray infrastructure has aggravated the impact of UHI and this has significant environmental consequences. In this regard green infrastructure is a practical and sustainable solution

2. THEORETICAL FRAMEWORK

Urban thermal environment

Urban Thermal Environment (UTE) examines the surface and air temperatures in urban areas and how it undergoes significant influences from man's degenerate activities due to changes in land use and land cover. The expansion of grey infrastructure such as roads, buildings and parking lot results in elevated temperatures (Li et al., 2022). This inadvertently leads to urban heat island, raising temperatures of urbans centres higher than their surrounding rural areas. The continuous expansion of urban areas, understanding the changes in the thermal environment is vital in developing effective mitigation strategies for the UHI effect. Elevated temperatures and the heightened occurrence of extreme climatic events linked to climate change intensify the influence of anthropogenic activities on the urban thermal environment. This contributes to increased energy generation and consumption, heightened demand for air conditioning, water usage, ecosystem balance, and a reduced overall quality of life (Zhang et al., 2024). Research indicates that urban temperatures will continue to rise with population growth, impacting the environmental comfort and residents (Zhang, Gu, et al., 2024). Therefore, UTE is not just about addressing urban heat island but also restoring indoor and outdoor thermal comfort.

Urban heat island (UHI) effect

The Urban Heat Island (UHI) refers to the phenomenon where urban areas experience higher temperatures than the surrounding rural areas, both during the day and at night. The key drivers for this disparity include vegetation removal, increased impermeable surfaces, construction materials with high heat capacity and low reflectance, dense urban arrangement, heat generation, and air pollution (Kumar et al., 2024). As cities continue to expand, the UHI effect has become a critical environmental and public health concern, contributing to increased energy demand, deteriorating air quality, and heightened thermal discomfort.

The issue of UHI is crucial especially with challenges posed by climate change and the rise of heat waves in urban areas. This place urban dwellers at a greater risk of heat-related diseases and deaths (Yang et al., 2024). It is important to understand the scale of heat production and retention in urban areas in developing strategies for UHI adaptation. Moreover, empirical solutions to UHI effect offers co-benefits, including improved air quality, reduced greenhouse gas emissions and enhanced urban liveability. Therefore, addressing mitigation of UHI effect foster more resilient cities.

Green infrastructure for UHI mitigation

A characteristic manifestation of changes in the urban thermal environment is the development of the Urban Heat Island (UHI) phenomenon. GI incorporates natural systems that help mitigate urban heat island effect. These systems include green roofs, rain gardens, street trees and parks, vertical gardens, and creating wet lands. GI cools the air by evapotranspiration, provides shade from trees and improves building insulation, thereby reducing surface and air temperatures in urban areas (Lin & Li, 2025). Recent studies have shown an increased research interest in the use of green infrastructure to mitigate the UHI effect (Lian et al., 2025). Countries like Singapore, have successfully integrated green infrastructure in creating optimum urban environments and mitigating UHI effect. GI have a long-term and sustainable positive effect on the urban environment ecosystem. Effective and functional combination of grey and green infrastructure is key to sustainable development, climate change adaptation and environmental sustainability.

The planning and design of green–grey infrastructure are inherently multifaceted processes that require consideration of multiple factors, including local climatic conditions, the extent of urbanization, patterns of land use, and the availability of economic resources (Zhou et al., 2025). The first step in implementation of GI is identifying priority area, step two is to maximize cooling value of existing GI, the third step is to develop a hierarchy of streets for priority GI implementation. Finally, select green infrastructure for areas based on guiding principles (Norton et al., 2013). The effectiveness of this implementation varies by location. The optimal placement of both green-grey infrastructure is crucial for mitigating urban heat island effect.

Urbanization and green infrastructure

Green infrastructure serves as an efficient strategy for reducing heat accumulation within urban environments (Norton et al., 2013). Urban environments display considerable heterogeneity, reflected in differences in population density, land-use configurations, climatic conditions, and socio-economic characteristics. These factors play a pivotal role in influencing the design, implementation, and overall efficacy of green infrastructure (GI). In urban centres characterized by copious grey infrastructure, adopting green infrastructure into the urban fabric requires careful planning. It should not only address issues of urban heat but also provide complimentary advantages such enhancing urban hydrology, improving air quality and enhancing overall well-being of individuals. GI enhances cooling through vegetation while providing a range of additional environmental and social benefits, all with substantially lower energy consumption and greenhouse gas emissions compared to conventional approaches such as air conditioning (J & Pradhan, 2025).

The implementation of green infrastructure in urban areas presents considerable challenges compared to rural settings, where greater land availability, lower population density, and increased flexibility in selecting appropriate GI strategies facilitate easier adoption (Wang et al., 2024). The predominance of grey infrastructure and complex government policies further complicate the planning and implementation of GI in urban areas (Seidu et al., 2025). Moreover, the retrofitting of existing built environment to accommodate green infrastructure usually involve cost of installation. Despite these constraints, the integration of GI in urban areas remains essential, as it is a sure path to urban resilience. It is therefore crucial to adopt a framework that ensures green infrastructure (GI) interventions are both effective and contextually responsive, thereby enabling optimal functionality and performance.

Given the complexity of urban systems, GI solutions must be tailored to local environmental, social, and economic conditions rather than relying on an objective approach (Rodrigues et al., 2025). Context-specific framework makes it easier to combine environmental ideas with the urban fabric, helping cities achieve effective adaptation (Herath & Bai, 2024). Furthermore, such a framework encourages interdisciplinary collaboration among urban planners, landscape architects, and policymakers to align GI strategy with broader urban sustainability goals. By basing green infrastructure projects on local conditions, urban areas can get the most out of them. Ultimately, adopting a context-sensitive approach to GI planning represents a critical step toward building in achieving desired effects – mitigating UHI effect and urban resilience.

3. CONCLUSION

Green Infrastructure have become increasingly vital in response to the urban heat island effect which is exacerbated by rapid urbanization and climate change. This review has examined the role of GI in addressing elevated urban temperatures, emphasing its importance in mitigating UHI effect. GI, through strategies such as green open spaces, trees, green roofs, vertical greening systems, provides a sustainable and pragmatic solution in balancing urban thermal environment. In addition to its environmental benefits, GI contributes significantly to the social and economic quality of urban areas by enhancing air quality, providing recreational spaces, and effective stormwater management. Urban planners, engineers, and policy makers should prioritize the integration of these systems in the built environment. The development of supportive policies and incentive is crucial for advancing the adoption of green infrastructure and optimizing benefits. Collaboration between governmental bodies, local authorities, and the private sector is vital in achieving urban resilience and environmental sustainability. Although the initial installation costs of green infrastructure (GI) may be substantial, these strategies offer considerable long-term savings through reduced maintenance expenses and lower infrastructure replacement costs.

In conclusion, effective and successful adoption of GI in the urban fabric presents a significant opportunity to mitigate urban heat island effect while fostering sustainable, resilient and liveable cities. Continued research, innovation, and cross-sector are essential to advancing these strategies and ensuring their successful implementation across diverse global contexts.

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