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Mitigating Urban Heat Islands: The Role of Green Building Strategies

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Review Article

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ABSTRACT

The combined effects of local warming brought on by urbanisation and global climate change are making urban heat a growing problem for many cities. Urban heat-related issues must be addressed immediately because these phenomena have substantial negative effects on the environment, the economy, society, and human health. Although buildings play a significant role in urban heat, they also offer opportunities for mitigation through the decarbonisation of the built environment. The building industry has acknowledged green buildings (GBs) as an innovative philosophy and practice. GBs have been suggested as a way to reduce the effects of urban heat islands (UHI) and other heat-related issues. The purpose of this study is to identify the most important architectural factors of green buildings that effectively reduce UHI. Using an extensive literature review methodology, the study identified eighteen important references following a thorough screening of more than 1400 preliminary studies. These sources concentrate on the ways that green buildings mitigate urban heat through different approaches, such as cutting carbon

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emissions, lessening the effects of artificial landscapes, and enhancing energy efficiency. The findings indicate that GBs significantly contribute to reducing the urban heat problem by lowering carbon emissions, minimising artificial landscapes, and promoting energy-efficient designs. This review provides a holistic analysis of the role of GBs in urban heat mitigation, aiming to inform future research in urban planning and green building development. This manuscript addresses a critical topic for the scientific and urban planning community. It highlights the role of green buildings (GBs) in mitigating the Urban Heat Island (UHI) effect, which is essential for combating climate change. The thorough literature review provides useful insights and identifies key strategies, such as green roofs and green infrastructure. It is valuable for researchers, policymakers, and practitioners in urban development and climate resilience.

Keywords: Urban heat island; green building; mitigation strategies; green infrastructure; climate change.

ABBREVIATIONS

UHI	:	*Urban Heat Island*
UHM	:	*Urban Heat Mitigation*
UHMA	:	*Urban Heat Mitigation and Adaptation*
HWs	:	*Heat Waves*
GBs	:	*Green Buildings*
AC	:	*Air Conditioning*
CO_2	:	*Carbon Dioxide*
NZEB	:	*Nearly Zero-Emission Buildings*
GI	:	*Green Infrastructure*
LEED	:	*Leadership in Energy and Environmental Design*
CASBEE	:	*Comprehensive Assessment System for Built Environment Efficiency*
BREEAM	:	*Building Research Establishment Environmental Assessment Method*
LCA	:	*Life Cycle Assessment*
LCC	:	*Life Cycle Costing*
SVF	:	*Sky View Factors*

1. INTRODUCTION

1.1 Preface

The substantial contribution of fossil fuels, particularly natural gas and oil, to carbon dioxide (CO_2) Carbon Dioxide emissions, which are intimately associated with global warming, has led to grave environmental concerns being raised by the fast rise in fossil fuel consumption. Global anthropogenic (CO_2) Carbon Dioxide emissions from fossil fuels increased by 1.2% in 2017 over the previous year. The Paris Agreement requires developed and developing nations to implement sustainable practices to mitigate climate change in response to rising global temperatures.

The management of air pollution sources is the primary goal of traditional pollution control strategies. These techniques efficiently reduce new pollutants but inadequately address existing atmospheric pollutants. First, the greenery incorporated into these structures stores carbon in plants and their roots by absorbing (CO2) Carbon Dioxide through photosynthesis. Second, vegetation in urban areas can lessen the amount of heat that buildings absorb (Sinha et al., 2013; Rebetez et al., 2008), thus lowering the energy demand for cooling. This reduction in energy consumption means fewer fossil fuels need to be burned, ultimately lowering global (CO2) Carbon Dioxide emissions (Frontczak & Isopescu, 2018).

Green roofs (GRs) offer a sustainable long-term solution for carbon sequestration in urban areas [20,28] Over the past decade, GRs have gained global recognition for their environmental and social benefits, helping mitigate the negative impacts of urbanisation (Sinha et al., 2013; Shafique et al., 2018). The aim of this study is to examine the role and impact of green buildings and green roofs (eco- environmentally friendly buildings) in mitigating urban heat island (UHI) effects and improving environmental quality in cities and the most important factors of green building which can be impactful for reducing UHI. The importance of this topic has intensified, especially in the current era, given climate change, rising temperatures, and environmental concerns. This research seeks to review previous studies2004-2024 and evaluate their findings to propose effective and practical solutions for various cities and geographical regions.

1.1.1 Green building

The growing conflict between rapid construction expansion and environmental degradation has led to a significant increase in interest in the concept of green buildings (GB) in recent years. Throughout all phases of their life cycle, including design, construction, operation, maintenance, and demolition, green buildings (GBs) are specifically made to reduce their impact on climate change and preserve natural resources. From location planning and development to maintenance and deconstruction, these buildings employ sustainable practices that efficiently manage the environment. Studies have indicated that green buildings (GBs) have several advantages, including encouraging material reuse, increasing energy efficiency, boosting ecosystems, facilitating sustainable land use, and lowering waste and CO2 emissions. Notwithstanding these advantages, green buildings (GBs) encounter various obstacles impeding their extensive implementation. These consist of the absence of cutting-edge technology, protracted investment recovery times, and inadequate information sharing (Gartland, 2012; Akbari et al., 2001). Because of this, GBs are not yet accepted as a common architectural solution by the general public. Furthermore, a large portion of the research that has already been done on GBs is fragmented, frequently concentrating on particulars without offering a thorough analysis, and restricted to particular areas or nations, which limits its applicability globally. Literature gaps are lacksa holistic and comprehensive understanding of the complexities between heat waves (HWs) and the built environment that is needed for planning and implementing effective mitigation measures in the future This paper fills these gaps by providing an engineering perspective evaluation of GBs and examining their role as an essential tool for sustainable development. In the midst of growing concerns about climate change and greenhouse gas emissions, it seeks to create a cogent and systematic framework for researchers, architects, and investors in the construction field. Crucially, in the context of sustainable design, this study also sets GBs apart from other notions like smart buildings, passive houses, and nearly zero-emission buildings (NZEBs). Industry stakeholders can benefit from the study's practical insights on green materials, certification schemes, and GB design.

1.1.2 Climate change

The Human Settlements, Energy, and Industry chapter came to the conclusion that the development of settlements is likely to be significantly impacted by climate change, especially in areas that depend on natural resources or are situated in coastal or riverine regions. The main concerns were about possible detrimental effects on development, like a settlement's decreased comparative advantage for economic growth in comparison to other places. Nonetheless, it was anticipated that certain regions would benefit. There are three main factors that make a settlement more vulnerable: its location, where flooding along rivers and coasts is most likely to occur; its economic dependence on weather-sensitive industries; and its size, where larger settlements are more likely to experience overall risks despite possibly having a higher capacity for adaptation (Alqahtani & Whyte, 2013; Arabi et al., 2015). These earlier findings were reaffirmed in the 2007 chapter on Industry, Settlements, and Society, which also emphasised the possibility for adaptation and explicitly placed the impacts of climate change within the framework of socioeconomic change.

However, the report also made the case that a large number of businesses, communities, and societies are highly adaptable. The competency and capacity of individuals, communities, businesses, and local governments, as well as their access to financial and other resources, will determine how much of this adaptation is made.

These include methods for handling uncertainty, approaches to spatial and temporal variation, valuation concerns covering market and non-market effects and indirect impacts on the economy, and treatment of scenarios that involve both climate and socioeconomic projections The way various types of climate signals are treated demonstrates the obvious need to take these factors into account in quantitative city-level analyses (Barrette et al., 2015; Bathaei & Abdel-Raheem, 2022; Bungau et al., 2022).

1.1.3 Urban heat

The Urban Heat Island (UHI) effect refers to the phenomenon where urban areas experience higher temperatures than their surrounding rural areas. In addition to heat, other factors contributing to this temperature increase include altered precipitation patterns, extreme weather events, and elevated air pollution in urban areas (Rosenthal et al., 2014; Chow et al., 2011). The difference in how solar radiation is absorbed in urban areas versus green spaces and residential districts, especially around roads, commercial, and industrial zones, is the main cause of the urban heat island (UHI) effect (Shafique et al., 2018; Escobedo et al., 2011). According to

(Rosenthal et al., 2014; Frontczak & Isopescu, 2018; Santamouris et al., 2014), the UHI effect is primarily a result of urbanisation, changes in land use, and industrialisation. It results from the replacement of heat-absorbing surfaces, the production of the UHI phenomenon affects cities worldwide, regardless of their size or location, though it is especially pronounced in megacities, particularly those in warmer climates (Ward et al., 2016; Rastinifard & Jomehpour, 2024; Santamouris et al., 2014). The UHI effect's most notable adverse effects include rising urban temperatures, which increase the likelihood of heatwaves. In turn, heatwaves are linked to increased rates of morbidity and mortality, discomfort in people, increased summertime energy use, and decreased quality of air and water (Hallegatte & Corfee-Morlot, 2010; Ken et al., 2020; Gago et al., 2013). Heatwaves pose serious health risks, particularly to vulnerable populations like the elderly, small children, people with physical or mental disabilities, and those who cannot afford mitigating measures like air conditioning (AC). The UHI effect is probably being exacerbated by the rise in global temperatures brought on by anthropogenic climate change, since its effects are being made worse by higher average temperatures and less precipitation. Additionally, climate change is anticipated to lead to more regular and intense heatwaves, with longer durations and more severe consequences for urban areas. Urban planning techniques have an impact on the UHI effect in addition to physical processes. The arrangement of urban areas and the UHI effect are highly correlated. The patterns of land use and land cover affect the wind and thermal properties of cities (Gartland, 2012; Rosenzweig et al., 2005). Increased evapotranspiration can help mitigate the UHI effect because vegetation releases latent heat and lowers the amount of energy needed for heating. Therefore, green areas can aid in cooling the surrounding area. According to (Hallegatte & Corfee-Morlot, 2010; Rosenthal et al., 2014) the natural process of tree transpiration is especially efficient at reducing temperatures. Furthermore, by converting solar radiation into other forms, vegetation helps to lessen its intensity. Reducing the production of anthropogenic heat is another method of mitigating the UHI effect. With strategies targeted at lessening its negative effects, urban planning plays a crucial role in UHI adaptation and mitigation, particularly in light of the growing effects of urban sprawl and climate change (Getter et al., 2009; Tiwari et al., 2020; Rizwan et al., 2008). One of the best ways to lessen the heat stress that city people experience is to increase the amount of green space and the percentage of vegetative cover. Thus, when planning future cities, urban planners must take the UHI effect into account and look for ways to lessen its effects in already-existing urban areas.

This study highlights the growing susceptibility of cities to the negative effects of urban heat by using a literature-based approach to examine the UHI issue. In order to demonstrate the issue's global scope, it examines trends in Germany and Australia, using both countries as examples. In order to identify similarities and differences, the paper also looks at and analyses UHI vulnerability assessments that have been published in the literature. It goes over how these vulnerabilities are addressed by current mitigation and adaptation strategies in brief. In order to improve urban resilience to the UHI effect, the paper concludes that a deeper comprehension of the UHI phenomenon is required, taking into account the unique context of each city, including social factors.

The UHI effect is closely related to urban sprawl, global warming, and unsustainable development practices; it is not a standalone issue. The UHI effect is predicted to worsen due to rising global temperatures, especially in cities that already experience heatwaves and high summertime energy demands. Furthermore, fast growing cities—especially those in developing countries—may be more susceptible to the negative effects of urbanisation if proper planning and funding for green infrastructure aren't provided. In light of the increasing frequency of heatwaves anticipated in future climate change scenarios, mitigating urban heat island (UHI) vulnerability is imperative for preserving public health, enhancing urban liveability, and decreasing urban energy consumption.

Developing green infrastructure and urban planning are the most promising approaches to reducing the UHI effect. A greater number of parks, green roofs, and urban forests are examples of strategies that can provide shade, lower surface temperatures, and encourage evapotranspiration cooling. In a similar vein, adding water features to urban areas can strengthen their ability to cool down and fortify them against temperature increases. In densely populated areas, wind corridors and heat-reflective building materials can improve airflow

and decrease heat absorption, which further mitigates the urban heat island (UHI) effect.
In conclusion, combating the UHI effect necessitates a multimodal strategy that incorporates legislative, social, and physical interventions. In order to support future urban development, urban planners must acknowledge the UHI effect and make sure that mitigation measures are included in city planning. Furthermore, a deeper comprehension of the UHI effect is required as cities grow and adjust to climate change, especially in relation to how it interacts with other urban stressors like air pollution, water scarcity, and socioeconomic inequality. Cities can become more livable, sustainable, and resilient in the face of rising global temperatures by tackling these issues.

Heatwaves' detrimental effects on urban health are a significant problem that will probably get worse as global warming continues (Rosenzweig et al., 2005). Rapid urbanisation has drastically changed the local ecosystems, landscapes, and population, which may have an impact on heat vulnerability (European Environment Agency [EEA], n.d.). During heatwaves, heat-related health risks—such as respiratory and cardiovascular issues—are frequently the cause of death (Hsieh & Huang, 2016; Ramamurthy & Sangobanwo, 2016) +mphasising that while knowing a person's unique biomedical susceptibility to heat is important, location and other external factors also affect risk levels. Since not everyone is at the same risk for health problems, cities must identify the populations that are most at risk. This makes it possible for legislators and urban planners to allocate resources more effectively. For example, social disparities and heat exposure are highly correlated in Phoenix, Arizona. Richer inhabitants, according to (European Environment Agency [EEA], n.d.), made use of their financial standing to keep low-density housing with irrigated vegetation, which helped to reduce heat stress (European Environment Agency [EEA], n.d.).

A number of studies have determined the main risk factors for the vulnerability to heat stress. These comprise people over 65, those taking medications that impair thermoregulation, small children, those with obesity, and those with pre-existing cardiovascular or respiratory conditions (Rosenzweig et al., 2005; Ke, 1982) assert that it is critical for local actors to comprehend the unique risks associated with climate change in their area and to pinpoint the factors that contribute to urban vulnerability. To effectively communicate with decision-makers, evaluate adaptation options, and develop timely and cost-effective responses, local authorities must have a deeper understanding of the drivers of climate change impacts (Ke, 1982).

In order to create the knowledge base required for successful adaptation management strategies, there is also a need for improved communication between climate change scientists, impact experts, and both local and national decision-makers (Ke, 1982; Khan et al., 2019). The identification of areas that are especially vulnerable needs to be part of this knowledge base (European Environment Agency [EEA], n.d.). A better knowledge of the factors contributing to spatial heterogeneity in heat-related deaths will aid cities in identifying the regions and demographic groups most at risk when they create plans for climate adaptation. Furthermore helping to adjust exposures to these risks will be this (Rosenzweig et al., 2005).

Policies that enhance social integration and cohesion in neighborhoods by widely disseminating knowledge about heat-stress mitigation could be one successful tactic (European Environment Agency [EEA], n.d.). Heat mitigation strategies need to be customised for individual vulnerable populations because vulnerability fluctuates over time and space and is not equally distributed among demographic groups (European Environment Agency [EEA], n.d.; Pheng Low et al., 2014). It is crucial to realise that a system's vulnerability is dynamic in order to handle uncertainty in an efficient manner. If a system does not adjust to new developments, it could become more vulnerable in the future even though it is currently robust. Vulnerability assessments need to take into account potential outcomes for a population in the event of a future disaster). This implies that vulnerability assessments should take into consideration how well societies and communities can adjust to anticipated future changes. Long-term solutions must be developed, and financial and spatial resources set aside for future adaptations, even though the scope and nature of future challenges remain uncertain. According to (Kumar et al., 2024), such adaptations should ideally offer co-benefits like enhanced ecosystem services, energy security, and water security in addition to mitigating the direct and indirect effects of climate change.

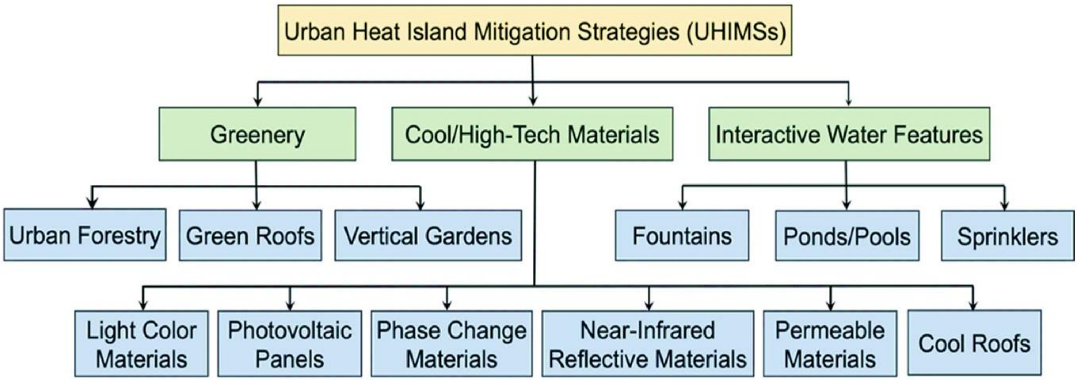

Fig. 1. Urban Heat Island Mitigation Strategies (UHIMSs) adapted from (Balany et al., 2020)

Urban ecosystems require green infrastructure (GI) to perform a variety of tasks, including regulating ecosystems, mitigating urban heat island effect (UHI), adapting to climate change, and providing important benefits and values. GIs come in a variety of forms, sizes, locations, and functions. These natural components have the ability to optimise, repair, and regulate urban structures, promoting sustainable urban growth. Planning various GI types is made easier by the knowledge that the size and structure of the GI dictate its ecological functions. GI can provide ecosystem services, like shading and lowering solar radiation, that control UHI. Urban planners can more accurately forecast how GI will provide ecosystem services and how these services will be impacted by climate change by knowing the roles GI plays in mitigating UHI. Given the importance of this information for adapting to climate change, GI is an important area of study for urban ecological systems. Furthermore, the ecological advantages and values of GI offer logical cues that support the argument for its significance in UHI mitigation. These advantages not only make GI's function clearer but also present chances for public servants, urban planners, and government officials to comprehend GI's importance. By incorporating these insights into planning, cities can build effective GI to achieve the maximum ecological benefits, which is key to the sustainable development of urban ecosystems Fig. 1.

1.1.4 Relationship between urban heat and GB

The use of green buildings (GBs) has become increasingly important in tackling the twin problems of urban heat mitigation and adaptation (UHMA) and global warming. The interaction of heat waves (HWs) and urban heat islands (UHIs) exacerbates temperature increases, which pose significant threats to human health by increasing morbidity and mortality. Heat waves (HWs) are already among the deadliest natural disasters in the United States, Australia, and the United Kingdom, are anticipated to deteriorate as a result of climate change. Furthermore, by increasing energy and water consumption and putting inhabitants under thermal stress, the UHI phenomenon—where urban areas experience higher temperatures than their rural counterparts—further strains urban systems. It is imperative to lessen the effects of UHI and help cities adjust to the challenges posed by heat, especially in rapidly urbanising regions of Asia and Africa.

In order to address the causes of heat waves (HWs) and urban heat islands (UHI), three main strategies have been proposed: cutting carbon emissions, putting heat adaptation plans into action, and implementing heat mitigation techniques. The first strategy aims to mitigate climate change by reducing carbon emissions, which should reduce the frequency and intensity of high-wind events. This is in line with global climate initiatives such as the United Nations Sustainable Development Goals and the Paris Agreement; however, the pace and scale of current actions are still insufficient.

Global adoption of adaptation techniques has included the widespread use of air conditioning (AC) and heating systems. Globally, there were 575.69 million AC units in 1990; by 2020, that number had increased to 1.93 billion, and by 2050, estimates showed that there would be 5.58 billion. Although using an air conditioner reduces heat stress, it also dramatically increases energy consumption, which exacerbates urban heat-related problems. This emphasises how urgent it is to design environments that are heat-resistant and don't rely unduly on AC-dependent solutions. The third option, known as heat mitigation, consists of a number of techniques meant to lessen heat sources and enhance heat dissipation. In order to improve shading and ventilation, these strategies include using cool materials, creating green and blue infrastructure, and strategically designing buildings and urban forms (Shafique et al., 2018; Kumar et al., 2024). Although these mitigation strategies have been developed, there is still a need for them to be implemented more effectively because of their limited widespread adoption.

By using co-benefit strategies, addressing urban heat challenges also offers chances to address other urban problems like air pollution and flooding. Urban heat stress and carbon emissions are closely related to the building and construction industry. Buildings account for 38% of the world's CO2 emissions. Nevertheless, buildings also present a great opportunity to apply heat mitigation strategies, such as cool materials, green and blue infrastructures, and passive design principles, to lower energy consumption and improve thermal comfort (Khan et al., 2019; Kumar et al., 2024; Ward et al., 2016). Therefore, to address the challenges posed by urban heat, innovative practices within the building and construction sector are required.

Green building (GB) techniques are widely acknowledged as a model for sustainability, providing environments that are secure, robust, and habitable. GBs offer a useful way to incorporate the previously mentioned solutions into actual situations. For example, GBs typically had temperatures 0.35°C cooler than conventional buildings, according to a study. According to (Khan et al., 2019), cities should implement deep green building (GB) design strategies, such as guaranteeing solar access for all new construction and utilising passive cooling methods to lessen the effects of UHI. These techniques can also improve indoor thermal comfort and reduce energy consumption, as demonstrated by zero-energy buildings in Stuttgart, Germany.

Mitigation of UHI is included in a number of green building (GB) assessment tools, including Comprehensive Assessment System for Built Environment Efficiency (CASBEE) in Japan and Leadership in Energy and Environmental Design (LEED) in the US. While CASBEE assesses attempts to reduce UHI through building design, Leadership in Energy and Environmental Design (LEED) suggests high albedo surfaces and vegetated roofs. UHI issues are also addressed by other tools, like Building Research Establishment Environmental Assessment Method (BREEAM) in the UK, Green Globes in the US The connection between GBs and urban heat, however, is still unclear. The relationship between UHI mitigation and GB elements, such as site configuration, building form, and occupant behaviour, has only recently been explored in studies on "zero UHI impact buildings" and "microclimate neutral buildings". Green buildings (GBs) possess the capability to tackle the problem of urban heat in various ways, including enhancing the quality of indoor environment, protecting natural resources, and encouraging water and energy conservation. The full life cycle of a GB—from site planning to construction and operation—can contribute to heat mitigation and adaptation. In this regard, GBs ought to be seen as a complete UHMA solution, able to address local and global warming while simultaneously improving resistance to heat stress. In conclusion, GBs offer a holistic approach to addressing the challenges posed by urban heat. By integrating sustainable building practices with heat mitigation and adaptation strategies, GBs can contribute to global efforts to reduce carbon emissions, alleviate local heat stress, and improve the quality of life in urban environments. This study provides a framework for understanding how GBs can address UHMA throughout their life cycle, offering valuable insights for future urban planning and development.

2. MATERIALS AND METHODS

The review draws on articles and reviews sourced from the Scopus database (1990–2024) concerning heat waves (HWs) and the built environment, using keywords such as “urban heat waves (HWs),” “built environment,” “green buildings,” “green infrastructure,” “climate change,” “building performance,” “energy consumption,” “heat mitigation,” and “community resilience.” Following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, a systematic search was conducted to identify relevant studies on topics including green buildings, green infrastructure, climate change, urban heat island (UHI) effects, and sustainable design, yielding an initial pool of 1,446 documents. After removing 511 duplicates and excluding 436 studies based on low relevance, an additional 364 records were filtered out due to incomplete text or lack of

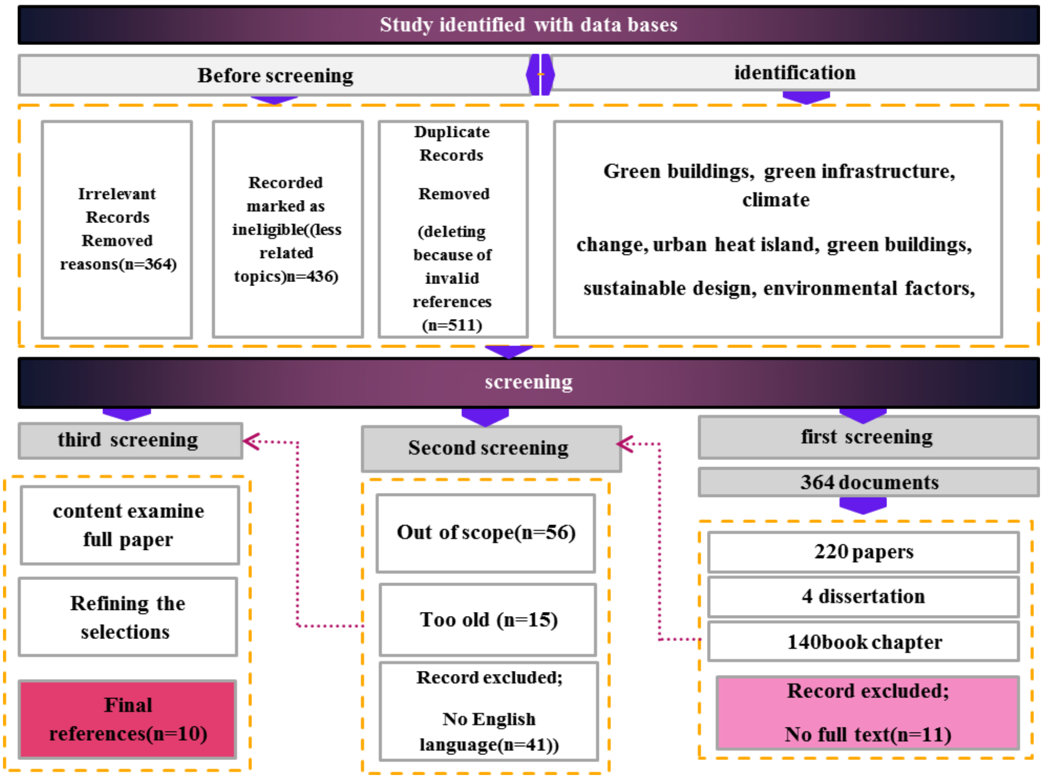

Fig. 2. Analytical procedure

pertinence, leaving 364 documents for screening. The first screening step included 140 book chapters, 4 dissertations, and 220 journal articles, from which 11 records were removed due to unavailability. A second screening excluded 56 studies for being out of scope, 15 for being outdated, and 41 for being in non-English languages. The remaining documents underwent a thorough content review, resulting in 10 final references selected for their quality, relevance, and focus on sustainable design, urban heat island mitigation (UHIM), and green building strategies (GBS). This rigorous PRISMA-compliant methodology ensured the review utilised the most reliable, recent, and pertinent studies to inform its analysis and conclusions Fig. 2.

3. RESULTS AND DISCUSSION

The review highlights diverse strategies, methodologies, and outcomes from global studies on urban heat mitigation through green building and green infrastructure (GBGI) interventions, emphasising their significant potential in addressing urban heat islands (UHIs) and improving resilience to heat waves . Global frameworks underscore the importance of informed policies and comprehensive inventories to guide interventions, while localised strategies illustrate the necessity of adapting solutions to specific urban contexts. Green roofs emerge as a critical strategy for reducing temperatures and enhancing sustainability, while broader policy updates and standardisation are essential for maximising GBGI efficacy. Despite advancements, challenges remain in scaling interventions and integrating diverse methodologies, with studies calling for broader, multidisciplinary approaches. Integrating GBGI into urban planning is pivotal for fostering community resilience and sustainability, underscoring the need for innovative, standardised practices to create climate-adaptive cities at building, urban, and regional scales Tables 1,2.

The findings from this review highlight a wide range of green building (GB) strategies that contribute significantly to mitigating urban heat problems, especially those associated with the Urban Heat Island (UHI) effect. As cities face increasing pressure from both global climate change and local urbanisation, implementing green building practices has emerged as a vital solution for enhancing environmental, social, and economic resilience. This section discusses the key factors identified in the literature and their implications for addressing urban heat challenges.

3.1 Green Roofs as a Primary Strategy

Several studies, emphasise the effectiveness of green roofs in mitigating UHI and enhancing energy efficiency. Green roofs not only reduce heat gain by absorbing solar radiation but also lead to significant energy savings during cooling seasons, as shown by the results from both individual cities and broader regional analyses. Their widespread adoption can be instrumental in addressing UHI effects, especially in dense urban environments. For example, green roofs on buildings along urban corridors (Chow et al., 2011) have been shown to substantially lower local temperatures by transforming roof areas into green spaces.

3.2 Integration of Urban Forestry and Green Infrastructure

Urban forestry and green infrastructure play a crucial role in cooling urban areas. These strategies can also enhance the calibration of regional climate models by accounting for vegetation and other urban morphological factors. The use of nature-based solutions, provides a multifaceted approach to urban heat mitigation, improving public health, air quality, and overall quality of life in cities.

3.3 Energy Efficiency and Life Cycle Assessment (LCA)

A major theme emerging from the review is the integration of energy efficiency measures in green building design. Solar panels, highlighted by D'Incognito et al. (2015), have been shown to significantly decrease energy costs and CO2 emissions, contributing to both energy savings and carbon reduction. Additionally, life cycle assessment (LCA) practices provide a comprehensive approach to evaluating the long-term sustainability of buildings, from construction through operation and maintenance. The adoption of life cycle costing (LCC) and Life Cycle Assessment (LCA) techniques can not only enhance building performance but also demonstrate the economic benefits of green buildings to stakeholders.

3.4 Green Building Rating Systems

Rating systems, such as LEED, Building Research Establishment Environmental Assessment Method (BREEAM), and the Green Star System, play a crucial role in encouraging the adoption of green building practices. However, challenges remain, especially in developing countries where the adoption of these systems is still limited. By improving national green building rating systems to include Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) considerations, the economic viability of green buildings can be better demonstrated, attracting more stakeholders to invest in sustainable construction. The Green Star system in Australia, for instance, provides valuable insights into overcoming the barriers to achieving green certification and sets a benchmark for evaluating green building performance globally.

3.5 Impacts on Property Value and Urban Design

The impact of green buildings on property values is another important consideration (Bungau et al., 2022) identified that green infrastructure can lead to increased land value, improved public health, and better quality of life. This finding is particularly relevant for real estate developers and urban planners, as it demonstrates the long-term financial benefits of incorporating green building principles. Moreover, urban morphology indicators such as building height, density, and sky view factors (SVF) need to be considered to effectively mitigate the UHI effect (European Environment Agency [EEA], n.d.).

3.6 Cool Roofs and Heat-Related Mortality

The role of cool roofs in reducing heat-related mortality is significant, particularly in cities vulnerable to extreme heat events. cool roofs can offset up to 18% of heat-related mortality during summer months. This finding underscores the potential life-saving benefits of green building strategies, particularly in densely populated urban areas experiencing rising temperatures due to climate change.

3.7 Challenges and Barriers

Despite the clear benefits of green buildings, several barriers hinder their widespread adoption. One major challenge is the high transaction costs associated with green building construction, as noted by (Stewart & Oke, 2012). These costs can discourage developers from pursuing green building certifications, especially in regions where green infrastructure is not yet widely adopted. Additionally, there is often a lack of awareness and understanding of the full benefits of green buildings among stakeholders, which can slow progress towards greener urban environments.

Table 1. Key findings of green building

Title	GBGI type (location)	methodology	Key findings	References
Understanding the synergy between heat waves (HWs) and the built environment: a three decade systematic review informing policies for mitigating urban heat island (UHI) in cities	global	articles and reviews	formulation of informed policies to mitigate the adverse impacts of heat waves (HWs) on built surroundings	(Joshi et al., 2024)
Urban heat mitigation by green and blue infrastructure: Drivers, effectiveness, and future needs	global	Review of 51 GBGI types under 10, broad categories	GBGI heat mitigation inventory can assist policymakers and urban planners in prioritising effective interventions to reduce the risk of urban overheating, filling research gaps, and promoting community resilience.	(Kumar et al., 2024)
Green building: A comprehensive solution to urban heat	global	review	helps understand how GB techniques contribute to UHMA and provides a reference to the revision of the GB assessment system for addressing urban heat problems.	(He, 2022)
Green space-building integration for Urban Heat Island (UHI) mitigation: Insights from Beijing's fifth ring road district Author links open overlay panel	Beijing	Case study	The study suggests that low-temperature areas can inform the adjustment of built-up patterns in high-temperature areas, offering a strategy for thermal environment optimization within specific green space coverage intervals.	(Yen et al., 2016)
Innovate green building for urban heat mitigation and adaptation (UHMA)	global	-	tandards, regulations, models, and paradigms should be updated and renewed. Assessment standards should define heat-related goals, targets, indicators, and techniques.	(He, 2024)
Green Infrastructure as an Urban Heat Island Mitigation (UHIM) Strategy—A Review	global	review	the majority of the research was conducted on a limited spatial scale and focused on temperature and human thermal comfort	(Balany et al., 2020)
Mitigating urban heat island through green roofs. Current World Environment	global	review	using green roofs as a main strategy for decreasing the harmful impacts of UHI especially the high air temperatures as well as their ability to add to the greening of cities	(Arabi et al., 2015)
Urban Heat Island (UHI) Mitigating Strategies: A	Global	review	some practical suggestions are provided to help	(O'Malley et

Title	GBGI type (location)	methodology	Key findings	References
Case-based Comparative Analysis			improve the resilience of tested UHI mitigation strategies in this study	al., 2015)
Sustainable Mitigation Strategies for Urban Heat Island (UHI) Effects in Urban Areas	Global	review	Sustainable greenery mitigation measures will be bolstered by the replacement of roads and pavements for walkers in highly urbanised areas with green installations	(Irfeey et al., 2023)
Green Buildings as an Accelerator in Climate Change Mitigation and Air Quality Improvement	Gauteng	Case study	the Gauteng government review and develop robust policies to increase investment in green buildings.	(Mukwevho et al., 2023)
The impacts of existing and hypothetical green infrastructure scenarios on urban heat island (UHI) formation	Guildford	Case study	Green roofs can act as an additional mitigation measure for the reduction of UHI at city scale if large areas are covered.	(Wang et al., 2024)

Table 2. Main factors of green building adapted from (Joshi et al., 2024)

Location	Strategy	Mitigation Potential	References	Scale
California, US	High thermal mass envelopes in conjunction with night ventilation	Indoor maximum temperatures maintained up to 24 °C, well within comfort zone limits on heat wave days.	(Akbari et al., 2001)	Building
Phoenix, US	Urban heat island research	Understanding urban heat islands (UHI) to inform policy applications.	(Chow et al., 2011)	City
Singapore	Green building principles	Enhanced sustainability and reduced environmental impacts.	(Pheng Low et al., 2014)	Building
Europe	Use of cool materials	Improved thermal comfort conditions and reduced heat island effects.	(Santamouris et al., 2014)	Urban
New York City, US	Urban forestry, living roofs, and light surfaces	Reduced urban heat island (UHI) intensity and enhanced environmental sustainability.	(Rosenzweig et al., 2005)	City
Global	Advanced cool materials	Enhanced urban thermal comfort and reduced cooling energy demand.	(Santamouris et al., 2011)	Urban
Global	Urban green infrastructure	Bridging biodiversity conservation and sustainable development through adaptive management approaches.	(Wang et al., 2024)	City
Europe	Drivers of heat waves (HWs) and urban heat islands (UHI)	Identified relevant drivers and proposed mitigation strategies.	(Ward et al., 2016)	Regional
Various	Green buildings	Comprehensive solution to urban heat mitigation through sustainability.	(He, 2022)	Building

Location	Strategy	Mitigation Potential	References	Scale
New York City, US	Urban heat mitigation strategies	Policy and practical measures for reducing heat impacts.	(Rosenthal et al., 2014)	Urban
Global	Carbon sequestration via green roofs	Potential to offset carbon emissions and mitigate heat island effects.	(Getter et al., 2009)	Building
Global	Factors affecting green building performance	Identified barriers and enablers to effective green building implementation.	(Yen et al., 2016)	Building

Table 3. Main factors of green building

Main green building factors
1) Factors Hindering green building performance: A review (Yen et al., 2016)
Best Factor: Green roofs lead to significant energy savings during cooling seasons.
2) Mitigating Urban Heat Island (UHI) Through Green Roofs (Alqahtani & Whyte, 2013)
Best Factor: Widespread adoption of green roofs as a primary strategy to mitigate the Urban Heat Island (UHI) effect.
3) Green Buildings as a Necessity for Sustainable Environment Development (Bungau et al., 2017)
Best Factor: Integration of green materials and circular economy principles for long-term sustainability.
4) Mitigating New York city's heat island with urban forestry, living roofs, and light surfaces (Rosenzweig et al., 2005)
Best Factor: Maintenance and life cycle assessment practices enhance the sustainability of green buildings.
5) Evolution to Emergence of Green Buildings: A Review (Khan et al., 2019)
Best Factor: Adoption of green building tools and rating systems in developing countries enhances understanding of green building practices.
6) Developing a Research Framework for Green Maintainability of Buildings (Chew et al., 2017)
Best Factor: Integrating solar panels in green buildings can decrease energy costs and reduce CO2 emissions.
7) Actors and Barriers to the Adoption of LCC and LCA Techniques in the Built Environment (D'Incognito et al., 2015)
Best Factor: Urban morphology indicators (UMIs) like building height and density should be considered for UHI mitigation.
8) Evaluation of Non-Cost Factors Affecting the Life Cycle Cost (Alqahtani & Whyte, 2022)
Best Factor: Green infrastructure contributes to increased land value, quality of life, public health, and regulatory compliance.
9) Comparative Study of Project Management and Critical Success Factors (Pheng Low et al., 2014)
Best Factor: Cool roofs can offset a portion of the seasonal heat-related mortality in cities affected by UHI.

3.8 Circular Economy and Sustainable Development

Finally, integrating circular economy principles into green building design, is critical for achieving long-term sustainability. By using green materials and promoting recycling and reuse, green buildings can minimise waste and reduce their overall environmental impact. This approach not only contributes to urban heat mitigation but also aligns with broader global efforts to promote sustainable development and reduce resource consumption.

3.9 Implications for Future Research and Practice

This review highlights several key areas for future research and practical applications in the field of green building and urban heat mitigation. First, more research is needed to develop region-specific green building rating systems that incorporate local climatic conditions, building types, and cultural factors. Additionally, future studies should explore the long-term economic and environmental impacts of green buildings, particularly in terms of life cycle costing and assessment.

On a practical level, urban planners, architects, and policymakers should prioritise the implementation of green building strategies, particularly in cities facing severe UHI challenges. By adopting a holistic approach that integrates energy efficiency, green infrastructure, and nature-based solutions, cities can enhance their resilience to climate change and create healthier, more sustainable urban environments Tables 1,2,3.

4. CONCLUSION

This review paper systematically explores the role of Green Buildings (GBs) in addressing the growing urban heat problems caused by the dual pressures of global climate change and local urbanisation. Through an extensive screening of academic literature, this study identifies and analyses key factors contributing to highlighting the critical need for sustainable solutions within the built environment. Green Buildings, with their innovative design principles, provide an essential pathway for mitigating the Urban Heat Island (UHI) effect and its associated environmental, economic, social, and health challenges.

The findings indicate that GBs significantly contribute to reducing the urban heat problem by lowering carbon emissions, minimising artificial landscapes, and promoting energy-efficient designs. The developed framework outlines GB responses to urban heat challenges across multiple aspects, including global and local warming mitigation, site planning, transportation, building design, energy and water efficiency, material selection, and life cycle management. By addressing these areas comprehensively, GBs can effectively reduce the adverse impacts of urban heat and enhance the sustainability of urban environments.

In conclusion, the integration of green building principles into urban development is vital for addressing the current and future challenges posed by urban heat. Policymakers, urban planners, and architects must adopt a holistic approach that incorporates GB strategies across all phases of a building's life cycle. This review provides a foundation for further research and practical applications, emphasising the importance of GBs in creating resilient and sustainable urban spaces capable of mitigating the negative impacts of urban heat.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology Details of the AI usage are given below:

1. ChatGPT

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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