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Understanding the synergy between heat waves and the built environment: a three-decade systematic review informing policies for mitigating urban heat island in cities

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Abstract
The escalating frequencies and intensities of heat waves have become a global concern in the face of climate change. Cities are increasingly vulnerable to overheating due to the amplification of urban heat island (UHI) during heat waves. Factors influencing the synergetic impact of UHI and heat waves on the built environment are complex, mainly including the degree of urbanization, land use patterns, building morphology, thermal properties of construction materials, and variations in moisture fluxes and heat sinks. Researchers worldwide are extensively exploring the characteristics of heat waves, the factors influencing heat waves in urban areas, and the impact of heat waves on built environments, as well as possible mitigation measures. However, the existing literature lacks a holistic and comprehensive understanding of the complexities between heat waves and the built environment that is needed for planning and implementing effective mitigation measures in the future. This study systematically presents a comprehensive overview of the global literature of the past three decades related to heat waves and urban built environments, spanning variations in heat wave definitions, factors influencing heat waves in urban areas, heat wave impacts on buildings, energy, occupant health, and infrastructure, mitigation measures, case studies, best practices, future considerations, and challenges. The objective is to synthesize current knowledge and highlight gaps in understanding, providing a foundation for future research. The review suggests that implementing a combination of strategies across various scales, from individual buildings to entire neighborhoods and cities, can contribute to effectively mitigating heat. This includes prioritizing compact and mid-rise buildings with light-colored exteriors, integrating large parks and green spaces, utilizing cool and super cool materials, ensuring effective insulation, employing passive and mixed-mode cooling and ventilation systems in buildings, and incorporating sustainable technology and innovation. Additionally, community participation and social equity are crucial for addressing vulnerabilities at a local level. It highlights the complexity of the relationship between heat waves and the built environment, emphasizing the need for interdisciplinary approaches for sustainable urban development in the face of heat waves. The outcomes can contribute to the formulation of informed policies to mitigate the adverse impacts of heat waves on built surroundings.

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Keywords Urban heat wave dynamics, Mitigation strategies and technologies, Energy-efficient urban design, Sustainable cooling solutions, Green and blue infrastructures, Advanced materials technology

Introduction

Heat waves, characterized by prolonged periods of excessively high temperatures, pose a formidable challenge to the built environment in cities in various ways. As climate change intensifies, the frequency and severity of heat waves are on the rise [1, 2]. UHI in cities wherein the temperature of urban areas is higher compared to surrounding rural areas is one of the major influencing factors for heat waves [3]. Heat waves have a synergetic effect with UHI phenomena further intensifying the magnitude of urban overheating globally up to 5–10 °C during heat waves [4, 5]. Land use planning and heat retention materials in built-up areas have a huge implication on the magnitude of UHI and subsequently the potential impacts of heat waves in cities [6–9]. As the cities become more urbanized the severity of impacts of combined effects of heat wave and UHI on built environment can exacerbate [10].

Understanding the synergistic impacts of heat waves and UHI on public health, building energy consumption, and infrastructure is essential for addressing related challenges and formulating effective mitigation strategies, given the crucial role of the built environment in mediating these impacts. Many studies have extensively documented increased health risk and excess mortality among vulnerable populations resulting from high ambient temperatures during the heat wave period, both in outdoor and indoor settings [11, 12]. For instance, there is an observed rise in heat-related morbidity during summer ranging from 0.05 to 4.6% per degree of temperature increase in Mekong River Delta, Madrid and Brisbane with an escalation ranging from 1 to 11% during heat wave period [4]. Moreover, increased ambient temperatures during heat wave periods raise the demand for building cooling energy in cities, resulting in an additional UHI induced Global Energy Penalty of up to 237 (± 130) kWh per person [13]. This could further result in elevated health risks for economically disadvantaged populations due to inequitable consumption of energy resources and substandard housing conditions [4, 14, 15]. Furthermore, elevated temperature levels during heat waves negatively impact infrastructure across power, healthcare, transportation, and water sectors in multiple ways [16, 17]. The interconnectedness of these sectors could further affect liveability of urban residents in the absence of incorporating eco-design principles, implementing sustainable operational practices and prioritizing heatwave-resilient maintenance strategies.

The exploration of heat waves and their interconnectedness with UHI has garnered significant attention from researchers worldwide. This inquiry extends to predictive studies, urban planning strategies, material engineering advancements, and innovative architectural designs, all aimed at mitigating the impacts of rising temperatures and enhancing urban resilience [5, 12, 18–20]. Predictive studies have forecasted a significant increase in days, frequency and duration of heat waves by the end of the century [1, 2]. At the urban planning and design level, substantial research is being done to demonstrate the effectiveness of various heat mitigation strategies aiming at limiting heat sources and enhancing heat sinks [10]. These strategies mainly include sustainable land use planning that integrates green infrastructure (GI) and blue infrastructure (BI) across various spatial scales, as well as increasing the albedo of roofs and pavements [4]. Advancements in material engineering with the development of supercool materials such as doped reflecting surfaces containing nano Phase Change Materials (PCM), quantum dots and fluorescent materials have demonstrated tremendous cooling potential with few practical challenges [21]. Architects have successfully experimented with innovative building design with contemporary applications of passive cooling strategies like vertical forests, supercool wind catchers, green facades, façade shading etc. that can significantly reduce peak cooling energy demands in buildings thereby providing promising solutions for heat wave mitigation at building scale [22, 23]. All these advancements represent a further grain of microclimatic responses and the clearer understanding on synergistic effects of heat waves and UHI on built surroundings can be obtained from them.

Despite substantial research and development on heat waves and UHI, a critical gap remains in understanding the complex interplay between these phenomena and their impacts on built environments. Perhaps, a connection may be established through co-evolutionary studies that adopt an eco-systemic approach, combining macroclimatic concerns with the microclimatic phenomena of UHI in diverse geographic and demographic settings. Current research often seems confined to individual domains such as urban planning, material engineering, and architectural design, lacking integration across various spatial scales. Consequently, there is a pressing need for interdisciplinary research that bridges these domains, fostering a comprehensive understanding necessary for developing effective mitigation measures tailored to the complexities of urban environments.

To address the aforementioned gap, this study systematically reviews global literature from 1990 to 2023 concerning heat waves and urban built environments. The primary objective is to synthesize existing knowledge, identify knowledge gaps, and discuss advancements in mitigation strategies. Through this, the study aims to lay the groundwork for future research and contribute to the formulation of effective policies to mitigate the impacts of combined effects of heat waves and UHI on built environments. The scope of the study includes a comprehensive review of various aspects related to heat waves and built environments. This encompasses discussions on heat wave definitions, urban factors influencing heat waves, their multifaceted impacts on health and energy, potential mitigation strategies, including successful applications at building and city scales and considerations for anticipated climate change impacts. Additionally, the study explores urban planning interventions that prioritize community resilience and social equity, emphasizing the need for interdisciplinary approaches to foster sustainable urban development in the face of heat waves.

Method

The review is based on the articles and reviews as referred from the Scopus database between 1990 to 2023 internationally concerning heat waves and built environment. The search strings used for searching the literature mainly included TITLE-ABS-KEY search for the key term “heat waves” with the “Boolean AND” operation with other keywords that included “definitions”, “built environment”, “buildings”, “infrastructure”, “health”, “building performance”, “energy consumption”, “indoor thermal comfort”, “heat mitigation”, “architectural designs”, “technologies”, “community resilience”, “social equity”. After removing the duplicate records, the remaining ones were screened mainly based on the titles, keywords and abstracts. The inclusion criteria at this stage were the relevance to the scope and objective of the study. The remaining records were then categorized into several thematic areas to facilitate discussion. Firstly, the variations in definitions based on thresholds, and characteristics of heat waves were examined. Secondly, factors influencing heat waves in urban areas were explored, including UHI, the contribution of building materials to heat retention and the implications of land use planning. Subsequently, the study delved into the multifaceted impacts of heat waves on the built environment, encompassing building performance, energy consumption, occupant health, and infrastructure. Following this, heat mitigation measures were considered, with a focus on strategies such as GI and BI, high albedo materials and sustainable building practices. Additionally, the study included case studies and best practices to provide real-world examples of successful interventions. Lastly, future prospects and challenges were addressed, including the anticipated effects of climate change on heat waves and built environments, potential advancements in technology, and the integration of community resilience and social equity in urban planning. The accessible full texts were then referred to and included in the discussion under identified themes. The inclusion criteria at this stage were robust methodology, relevant data and heterogeneous outcomes (Fig. 1).

The narrative synthesis involved the final sample size of 153 peer-reviewed articles. Figure 2 illustrates the distribution of these articles across different countries worldwide. Notably, research activities in this field were predominantly concentrated in the USA (40), Australia (26), China (24), and the UK (16).

Definition and characteristics of heat waves

Researchers have been investigating thresholds to define heat waves and their profound impacts on human health and the environment for several decades. However, the lack of a standardized definition for heat waves poses challenges in assessing patterns, trends, and impacts, leading to diverse perspectives among experts. Prevention measures and protective temperature thresholds are often defined based on descriptive analyses and expert judgment [24]. The correlation between mortality and heat waves varies significantly depending on how ‘heat wave’ is defined [25]. Despite these variations, numerous studies have examined patterns, trends, and disparities in the impacts of heat waves on mortality and morbidity across different demographics and geographic areas [18–20]. Variations in definitions and thresholds arise from the use of different air temperature metrics, including daily maximum, minimum, absolute, average, heat index, as well as climatic and bioclimatic indices as mentioned in Table 1.

Before 2010, there were limited studies critically examining the appropriateness of heat wave thresholds that were predominantly based on expert judgment. One of the earliest investigations occurred in 2001, evaluating and testing the effectiveness of existing thresholds in the United States [28]. In Nanjing, China, from 2007 to 2013, among the different heat wave definitions examined, those defined as lasting for four consecutive days or more with a daily average temperature demonstrated the highest suitability [25]. According to another study conducted in Wuhan, China, defining heat waves based on daily mean temperature with a duration exceeding three days demonstrated the highest predictive capability in assessing the mortality impacts of heat waves [19]. In the Coastal and Piedmont regions of North California, heat wave definitions were found to be most sensitive to daily maximum and daily minimum temperatures respectively for two or more consecutive days [31]. A comparison of official heat wave definitions derived from weather data for sixteen cities in France revealed that the most significant heat-related mortality impact was indicated

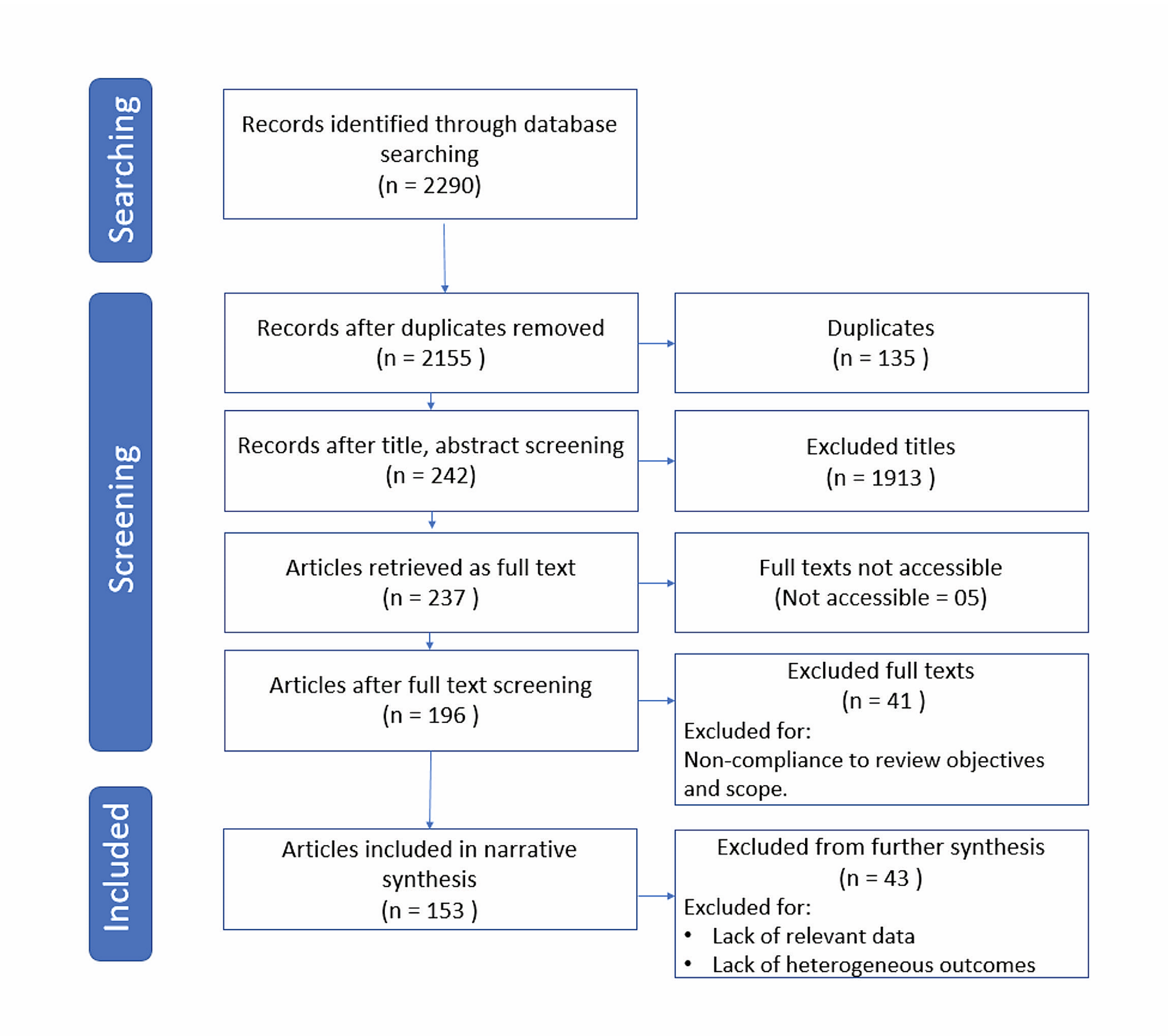

Fig. 1 ROSES flow diagram for literature screening

by the Excess Heat Factor (EHF). At the national level, the EHF identified heat waves with 2.46–8.18 times the global burden compared to the climatological indicator of the French National Weather Service and the heat wave indicator of the French National Heat Warning System, respectively [29]. Analysing daily maximum temperatures recorded at 587 surface observation stations in China from 1959 to 2013, it is suggested that, given the notable variations in regional climatology, employing relative thresholds is more meaningful for identifying local extremes [26]. The study sought to define heat waves in five Chinese cities and discovered a positive non-linear correlation between extremely high temperatures and mortality. City-specific definitions were established, such as Beijing and Tianjin defining heat waves as two or more consecutive days with daily mean temperatures exceeding 30.2 and 29.5 °C, respectively. For Nanjing, Shanghai, and Changsha, heat waves were defined as lasting three or more consecutive days with daily mean temperatures higher than 32.9, 32.3, and 34.5 °C, respectively [33]. Adjusting national-level thresholds to city-specific thresholds can provide a more accurate understanding of heat wave characteristics, particularly concerning demographic, climatic, and geographical differences.

The National Weather Service (NWS) HI thresholds derived from both ambient temperature and humidity are a general estimate indicating the onset of human physiological stress. In regions characterized by high heat and humidity, adjustments to these thresholds may be necessary for physical, social, and cultural adaptations, ensuring that only events perceived as stressful are accurately identified. For example, following the analysis

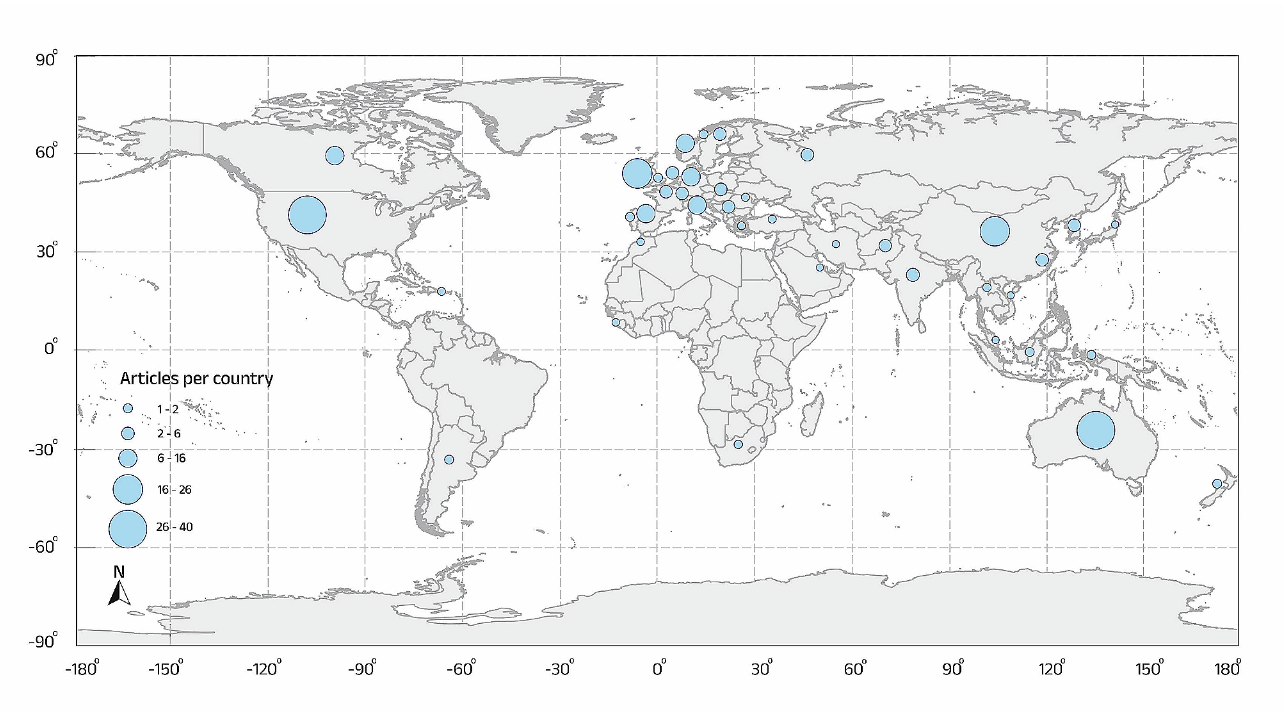

Fig. 2 The country-wise global distribution of the literature considered in the study

Table 1 Best suitable heat wave threshold criteria for different places

Location	Study period under consideration	Best suitable threshold criteria	Study reference
Nanjing, China	2007–2013	Daily average temperature	[25]
Wuhan, China	2003–2010	Daily mean temperature	[19]
China (5 Cities)	1959–2013	Daily mean temperature	[26]
China	1961–2014	Relative and absolute heat indices	[27]
United States	1951–1990	National weather service, heat index (HI)	[28]
France (16 cities)	2000–2015	Excess heat factor	[29]
France	1979–2002	Universal thermal climate index (UTCI)	[30]
Coastal and Piedmont region of North California	2011–2016	Daily maximum for Coastal and daily minimum temperatures for piedmont	[31]
South Korea	2011–2014	Wet bulb globe temperature (WBGT)	[32]

and testing of various thresholds in the United States for the period 1951–1990, a heat wave was defined as a duration of at least 48 hours during which neither the overnight low nor the daytime high falls below the NWS heat stress thresholds (80 and 105 °F, respectively) [28]. An examination of the temporal trends of heat waves in China spanning from 1961 to 2014 revealed divergent patterns related to relative and absolute heat indices. Notable correlations were identified among various HIs within the same category (either absolute or relative), but the connections were weak when comparing relative and absolute threshold HIs [27]. A study in South Korea recommends WBGT and its associated thresholds as the most appropriate for establishing connections between heat waves and heat-related diseases. When heat waves were defined using WBGT and HI, the study region experienced the highest total number of heat wave days, while the longest duration of heat waves was observed in the same region based on air temperature [32]. According to [30], using the UTCI is a meaningful threshold for a potential heat-health watch warning system [34]. proposed bioclimatic indices like the UTCI and Physiologically Equivalent Temperature (PET) as a new basis for heat wave definitions.

While mortality impacts are a significant focus of these studies, they also explore demographic, climatic, and geographical differences, employing diverse methodologies. It's essential to recognize that the implications of these findings extend beyond human mortality to include the built environment. Changes in the built environment over time affect climatic parameters, which in turn influence these indicators. Continuous monitoring and adjustment of thresholds are vital for informing effective heat mitigation measures for built environments, ultimately enhancing resilience.

Furthermore, understanding the association of long-term trends with different definitions of heat waves is crucial for comprehending the temporal and spatial characteristics of heat waves [35], especially in the context of the built environment. For example, on average, in Spain, the temperature threshold related to mortality has shown an increase at a rate of 0.57 °C per decade, over the period from 1983 to 2018 [36]. The research in the eastern Mediterranean region, from 1900 to 2019 concludes that changes in the timing of heat waves, consistently observed across 15 definitions, have led to the extension of the heat wave season by up to 7 days per decade since the 1960s [34]. This extension has critical implications for the built environment, emphasizing the necessity for buildings and infrastructure to mitigate prolonged periods of extreme heat.

A study based on the synoptic conditions characterizes a combination of daytime and night-time heat waves to form compound heat waves. Night-time and compound heat waves show more significant rises in both occurrence and proportion compared to daytime heat waves. Daytime heat waves are linked to heightened solar radiation during dry periods and decreased cloud cover and humidity under clear skies. On the other hand, night-time heat waves usually coincide with humid conditions, along with higher cloud coverage, humidity, and longwave radiation at night [37]. Understanding these dynamics is pivotal for devising effective heat mitigation strategies considering both daytime and night-time thermal comfort in the built environment in the face of heat waves. Conventional heat wave definitions have consistently centered around external conditions, yet it is the conditions within buildings that pose a substantial threat to human lives, leading to significant casualties. There is a need for a definition specifically addressing the performance of buildings in terms of overheating. Very few studies have addressed this concern [38]. has introduced a method to define heat waves based on their impact on indoor conditions and occupant well-being, shifting from an external to an internal perspective. This human-centric approach aims to assess building resilience and establish early warning systems for health emergencies. A case study based on four heat wave events in China finds that the severity of heat wave events, especially the most intense events based on the relative heat wave event definition using average temperature thresholds, is a more suitable definition that poses the greatest threat to indoor thermal conditions. Selection of extreme hot years based on heat wave severity indicates a potential 1–2 months of indoor overheating in passive buildings in specific cities by the century's end, emphasizing the necessity for adaptive measures in building design and urban planning [39].

Although there is an agreement in outcomes of various studies projecting a significant increase in days, frequency and duration of heat waves by the end of the century [1, 2], these studies differ significantly in the methods such as the duration of the period under consideration, assessment approaches.

A consistent framework for defining heat waves is necessary to compare and understand heat waves on a global scale, especially given the increasing concerns about global warming and its potential effects on the frequency, severity and duration of heat waves. However, examining the temporal progression of heat wave threshold temperatures, which exhibit geographic diversity, is crucial to devise heat adaptation plans. This evolution can be influenced by local demographic, socioeconomic and microclimatic diversities. Therefore, it is essential to acquire a thorough understanding of the specific local mechanisms, such as variations in moisture fluxes that contribute to various types of heat waves. This knowledge is crucial for informing future assessments of risks and impacts. Additionally, more research is needed to define occupant-centric heat wave thresholds for indoor built environments.

Factors influencing heat waves in urban areas

Numerous studies have demonstrated that urban areas are more vulnerable to heat wave impacts [12, 40, 41], compared to rural areas. For instance, notable increases in the frequency of heat waves were observed during 1973–2012 in 217 urban locations worldwide as studied by Mishra et al. [42] with almost half of the locations experiencing extremely hot days and two third locations experiencing increases in the frequency of extremely hot nights. July 1987 heat wave in Athens had a modifying impact by dense built structures in central urban areas than sub-urban regions causing high night time heat stress on people [43]. The morphological and construction features of cities, urban landscapes, land use patterns, and anthropogenic heat emissions play significant roles in determining the thermal equilibrium and local ambient temperature increase in urban areas [10]. This section examines these factors, focusing on UHI, the contribution of building materials in heat retention and the implications of land use configurations. By exploring these aspects, we aim to provide a comprehensive understanding of the complex dynamics contributing to heat wave vulnerability in urban areas.

The UHI phenomenon has been reported as a crucial factor that influences heat waves and their impacts on built environment in urban areas [3, 4]. Many studies conclude that UHI intensifies summer heat waves and raises energy usage and the risk of heat-related illnesses and deaths for vulnerable populations such as the elderly, young children, and low-income residents, who are more susceptible to extreme heat stress due to various physical, social, and economic factors [7, 44–46]. The extent of UHI, as measured in 101 cities and regions across Australia and Asia, is noteworthy, ranging between 0.4 to 11.0 K [47]. A study that mapped surface temperatures during the August 2003 heat wave in Paris supported the association of elevated night-time surface temperatures with high mortality risk attributed to UHI phenomena [3]. In China, night-time heat wave frequency, intensity and duration were observed to be increased with urbanization accounting for nearly 50% of the extended duration and nearly 40% of the enhanced intensity and frequency of night-time heat waves in urban areas relative to rural areas [48]. During the 1998 heat wave, the mortality rate in the urban zone in Shanghai was approximately 27.3 per 100,000 which was significantly higher than the rate of 7 per 100,000 in the outlying districts. The study concluded the direct influence of UHI on increased hot days and heat waves in urban areas compared to rural areas [49]. The primary contributors to UHI in urban areas are increased anthropogenic heat emissions, excess release of sensible heat from building materials, increased incoming long-wave radiation due to pollution, lowered evaporative heat loss, decreased turbulent transfer, and reduced longwave radiation losses from street canyons [6] as illustrated in Fig. 3. These are mainly dictated by the degree of urbanization, urban morphology, construction characteristics land use and land cover patterns in urban areas.

Heat waves and UHI share a synergistic relationship [5, 50]. Ambient temperatures in urban areas are intensified due to the combined effect of UHI and heat waves resulting in overheating. Also, heat waves interact with UHI, amplifying the temperature contrast between urban and rural areas and consequently leading to elevated heat-related consequences in cities [5]. A recent study in Beijing demonstrated seven times increase in the frequency of compound heat wave with the intensity increasing from 0.65 to 2.47 °C resulting from enhanced UHI during 2000–2018 [51]. The intensity of UHI was raised to about 0.9–1.3 °C during daytime under heat wave conditions studied over Mediterranean towns Nicosia, Cyprus during 2007–2014 [50]. Upper top layer soil moisture that dictates the evaporation losses in rural areas is mainly responsible for the enhancement or suppression effects of heat waves on urban heat islands. Reduced soil moisture in urban areas lowers evaporation losses thus enhancing the UHI [5, 50, 51]. In Beijing, daytime heat waves were noted to heighten the night-time UHI, primarily due to an escalation in the urban-rural contrast in sensible heat and a decrease in latent heat differences. Conversely, night-time heat waves were observed to suppress the daytime UHI. During the 1995 heat wave in Chicago, the UHI was observed to be prominent. Daytime maximum temperatures in the city centre (Midway) were 1.6 °C higher compared to nearby suburban and rural areas. At night, the city centre experienced

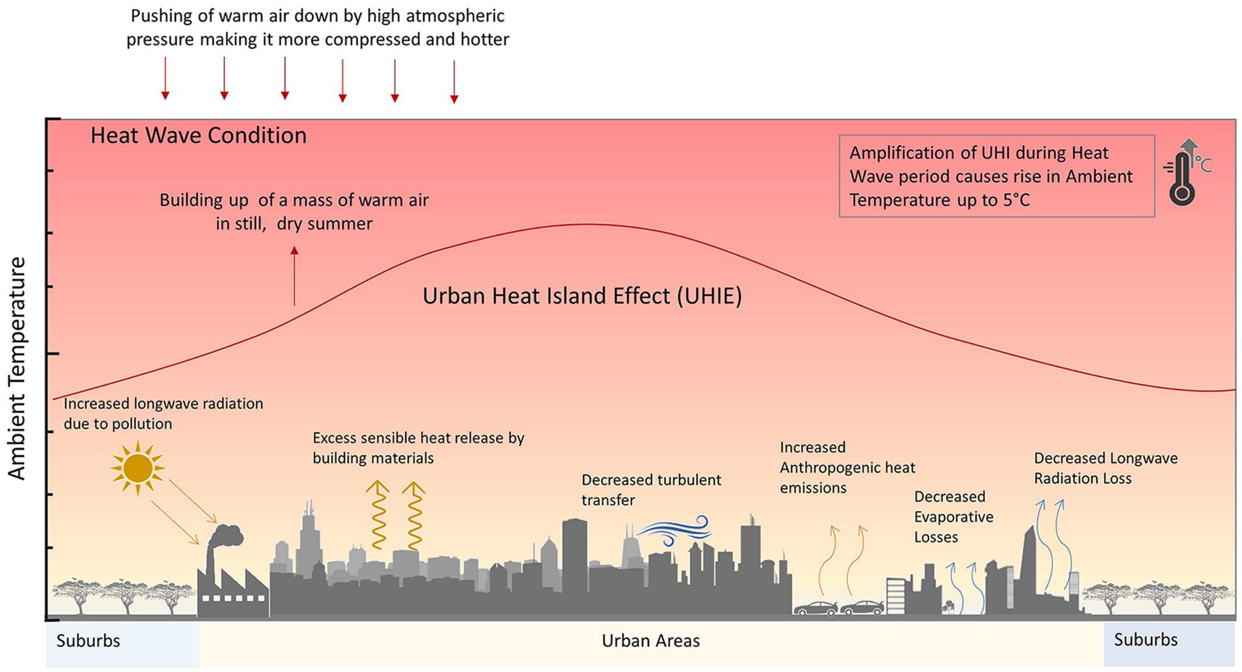

Fig. 3 Synergistic relationship between heat waves and UHI (Adapted from Santamouris [4] and Oke et al. [6])

a temperature difference of 2.0–2.5 °C, being warmer. Additionally, the city air was much drier during the daytime and moist during early mornings, compared to the surrounding rural areas [52]. Lower wind speed is another crucial attribute responsible for the enhanced synergetic impact of heat waves and UHI in urban areas [5], as wind speeds get altered due to urban morphology that often creates dense urban canyons hindering natural wind flows. The depletion of groundwater in urban areas can affect the intensity and frequency of heat waves, as the urban climate is influenced by near-surface weather conditions [10].

Multiple investigations indicate that the types and configurations of land use have a direct impact through elevated local temperatures, and an indirect impact through air pollution, on the thermal comfort and health of urban residents during heat wave days [7–9, 53]. A study in Berlin city by Dugord et al. [54] for a small temporal scale of 12 h revealed that the warmest land uses at both 10 am and 10 pm are associated with high construction and population density in industrial, commercial, residential and mixed-land use areas. Additionally, the type of residential construction also contributes to temperature differences, with closed constructions like multi-story tenement blocks exhibiting lower nocturnal cooling compared to open areas such as residential parks and sports, leisure, and recreation zones [55]. Another study in Shanghai city found that non-built-up open land uses such as agricultural, unfrosted green lands and urban brownfields exhibit elevated mean Land Surface Temperatures (LST) at 10 am, accompanied by significant variability in LST. However, water bodies display the least variability attributable to water's substantial specific heat capacity, resulting in a slower cooling rate [56]. City dwellers residing in densely populated areas at potentially the highest heat-stress risk independently from their location in the city, the natural characteristic of its surroundings, the state of the surfaces and the characteristics of the inhabitants [54]. A spatial heat stress pattern exhibited during heat waves in Beijing from 2008 to 2011, showed an elevated risk in urban areas, a moderate risk in the transition zone between urban and rural areas, and the lowest risk in rural areas [57]. Furthermore, meta-analysis of eleven studies focussing on intra-urban microclimate variations, estimated that individuals residing in warmer regions within cities experience a 6% increased risk of mortality or morbidity compared to those in cooler areas. Similarly, those living in less vegetated areas face a 5% higher risk compared to their counterparts in more vegetated areas [58].

In urban environments, the combination of high ambient temperatures and poor air quality during heat waves poses significant challenges to public health, exacerbated by the types and configurations of land use. For example, Thiassion, a Greek industrial area, experienced exceptionally high ambient temperatures and poor air quality causing prolonged thermal stress throughout the day in the 2007 heat wave. The Air Quality Stress Index (AQSI) indicating significant stress, ranged from 1.41 to 6.58 due to increased ozone concentration. Residential areas, especially those away from the seashore, experienced intense heat, with temperatures reaching up to 47.7 °C [59]. A GIS-based study conducted in urban areas in Germany identified augmented concentrations of health-relevant airborne substances such as metals and polycyclic aromatic hydrocarbons within the zone where there is an increased risk of the simultaneous occurrence of temperature stress and particulate matter pollution [8].

Built-up surfaces in urban areas including building envelopes (walls and roofs), roads, pathways, etc. retain, reflect and release heat depending on their thermal properties [6]. Built-up surfaces especially dark coloured asphalt roads and pavements having low albedo absorb more and reflect less incident solar radiation [60], resulting in excess heat retention in urban fabric. Asphalt pavements which are popularly used observed to have extremely high surface temperatures in open spaces in tropical environments during the daytime ranging from the lowest 24.6 °C in the morning to the highest 60.4 °C in the afternoon, indicating 35.8 °C temperature increase during the 6 hr period from 6.00 a.m. to 12.00 p.m [60]. Urban surfaces due to their roughness, tend to trap 10–40% excess solar radiation compared to flat surfaces composed of the same material [61, 62]. This is because roughness reduces the solar reflectivity of materials.

Materials having high thermal capacitance and low emissivity, absorb and store sensible heat during daytime and do not readily release to offset the surface radiative loss. This excess sensible heat is released at night thus adding to the nocturnal UHI [6]. During the heat wave period, this can result in the persistence of constantly high ambient temperatures during day and night time giving vulnerable populations less opportunity to recover from heat-related morbidity. This also results in increased cooling energy demand as cooling systems are operated for longer durations day and night for maintaining indoor thermal comfort conditions. A heavyweight building wall possesses distinct characteristics compared to a lightweight building wall, particularly concerning the processes of heat storage and release. A recent study demonstrated that, among the most commonly used wall façade systems in tropical climates, conventional uninsulated heavy-weight brick walls increase afternoon UHI compared to lightweight façade systems such as Aluminium Cladding Panel (ACP) and low-E glazing. This is because, due to their high thermal inertia, they store and release a significant amount of thermal energy outdoors in the afternoon. Additionally, the application of ACP insulation on brick walls can raise surrounding outdoor temperatures by up to 4 °C [63]. This can exacerbate outdoor heat in tropical urban areas during heat wave events in contrast to temperate urban areas where the effects may be less pronounced due to different climatic conditions. Also high reflectivity of lightweight walling systems can raise surrounding ambient temperatures in urban areas during heat wave periods leading to outdoor heat exposure for pedestrians. In practical terms, the interplay between building geometry and the thermal characteristics of diverse building materials occurs across a broad spectrum of combinations. Optimal pairings of these factors influence thermal characteristics within urban fabric specifically influencing night-time heat island conditions. The combination of these factors that maximizes the UHI effect can lead to an increase in temperature of up to 10 °C after sunset [6]. Tis facet needs to be investigated in detail in various urban climate settings. Furthermore, it's essential to recognize the distinctive challenges posed by heat waves in tropical urban areas compared to temperate regions. These challenges highlight the importance of tailored strategies for mitigating heatwave impacts in diverse urban contexts.

In summary, the factors influencing heat waves in urban areas encompass the complex interplay of UHI and heat waves that is influenced by the geographical location of an urban area, proximity to the city centre and water bodies, land use patterns, population density, built-up area density, building typology and thermal characteristics of building materials. However, research towards a comprehensive understanding of contributory aspects of these factors in varying urban settings is needed at micro-climate and macro-climate scales for effective urban planning and mitigating the adverse impacts of heat waves on urban residents.

Impacts of heat waves on the built environment

Numerous studies have assessed the implications of heat waves on various aspects of urban built environments such as building performance, building energy consumption, occupant health and infrastructure [11, 16, 64–66]. Technological advancements since 2010 have transformed research methodologies, shifting from reliance on field experiments to computational techniques, enabling simulation of diverse scenarios for indoor and outdoor thermal comfort conditions and energy consumption in buildings across historical, current, and future contexts. Figure 4, illustrates the impacts of synergies between heat waves and UHI on built environment.

Heat waves can significantly impact health within the built environment, especially in vulnerable populations [67–69]. Particularly in urban areas, the built environment aggravates the health impacts of heat waves by intensifying UHI [4]. This is primarily caused by dense construction, scarce green spaces, widespread use of heat-absorbing materials and poorly ventilated buildings, all of which contribute to heightened exposure of urban residents to extreme heat levels both indoors and

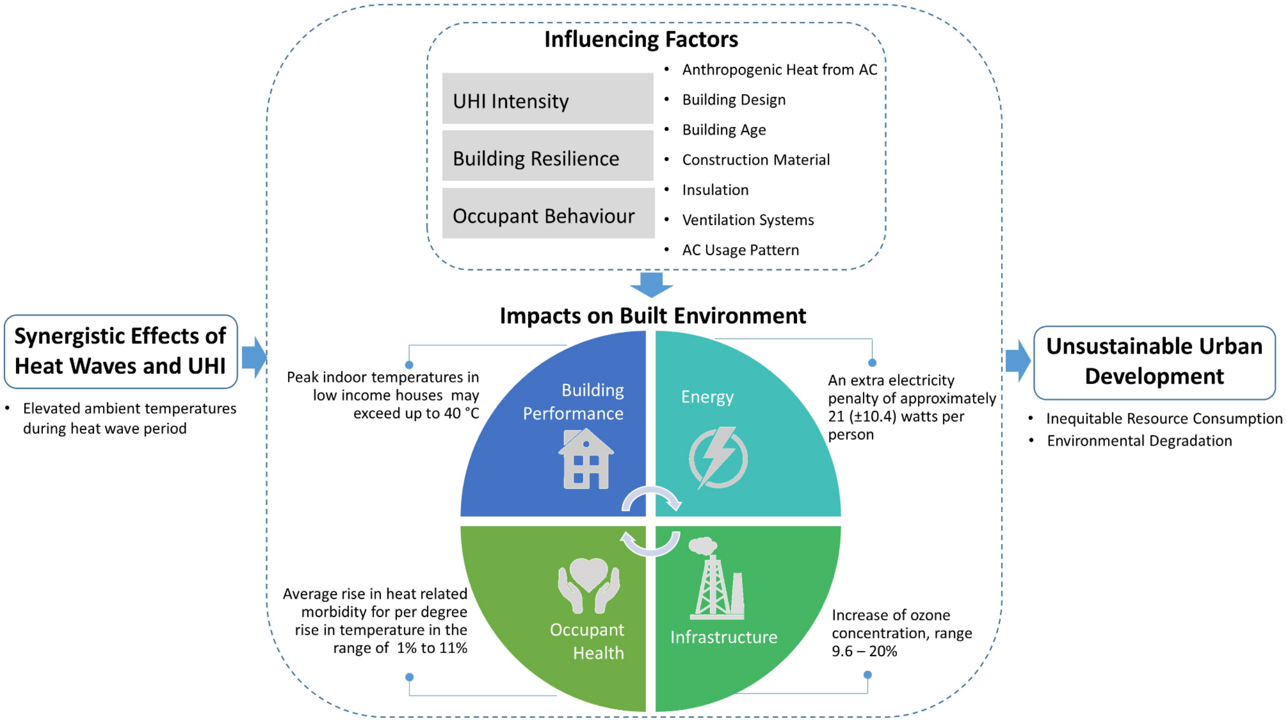

Fig. 4 Impacts of synergistic effects of heat waves and UHI on built environment (Adapted from Santamouris [4])

outdoors [9, 70, 71]. Consequently, several studies have explored the impact of high ambient temperatures, especially during heat waves in urban areas, on overall and cause-specific morbidity and mortality in urban areas [11, 12]. Some of the common impacts are sleep disturbances, fatigue, exacerbation of medical conditions, and fatalities attributed to heatstroke [72]. There is an observed rise in heat-related morbidity ranging from 0.05 to 4.6% per degree of temperature increase, with a higher increase during heat waves ranging from 1 to 11% [4]. Older women in urban areas are more susceptible during heat waves attributed to factors such as age, chronic illness, social isolation, inadequate access to and usage of air conditioning, and lack of awareness [11, 67, 73]. However, a study in Maricopa County found that the impact of extreme heat is nearly as significant among younger individuals as it is among older individuals, partly due to their frequent outdoor exposure [74]. Pediatric health issues linked to heat waves encompass renal disease, respiratory disease, electrolyte imbalance, and fever [75]. Moreover, many researchers have found a positive correlation between heatwave conditions and hospital admissions related to cardiovascular and respiratory diseases [68], mental, behavioural, and cognitive disorders [76]. Low-income group people show significantly high vulnerability to heatwave-induced mortality and morbidity due to poor indoor environment, deprivation of adequate mechanical cooling and healthcare facilities [4, 69]. High temperatures during heat waves have also been reported to reduce cognitive abilities and work efficiency of laborers due to limitations of human psychological mechanisms to cope with high-temperature conditions beyond the threshold [77]. A meta-analysis of nine studies found that individuals working in conditions of heat stress were nearly four times more prone to experiencing occupational heat strain compared to those working under thermally regulated conditions [77]. Additionally, occupants of poorly ventilated office buildings can get exposed to indoor air pollutants for a longer time thus affecting their health [9].

In this context, understanding how building characteristics and design influence resilience to heat waves is crucial for mitigating their impacts on indoor thermal discomfort and overall building performance, as heat waves pose significant challenges to buildings, leading to prolonged heat exposure for occupants [15, 78]. Research indicates that the performance of a building during heat waves is predominantly influenced by factors such as its envelope characteristics, insulation attributes, and ventilation systems [71, 79, 80]. Understanding how building characteristics and design influence resilience to heat waves is crucial for mitigating their impacts.

Findings of several case studies and experimental studies demonstrate variations in building resilience to heat waves based on envelope characteristics such as construction materials, building age, degree of insulation and envelope design. For example, research conducted during the August 2003 heat wave revealed notably uncomfortable indoor conditions in flats in London compared to two storey houses in Manchester during much of the heat wave period with variation in different rooms [14]. In another study in Australia during the summer of 2012, indoor temperatures among dwellings varied significantly attributed to structural features such as age, roof pitch, insulation where dwellings constructed with brick and veneer exhibited lesser diurnal temperature fluctuations compared to other building materials [71]. Traditional masonry wards in hospitals in UK National Health Service (NHS) hospital exhibited resilience to elevated temperatures for 2006 hot summer weather conditions in contrast to lightweight modular buildings that were projected to face a hazardous risk of overheating [81]. The findings of the study revealed that conventional uninsulated heavyweight brick walls, with their high thermal inertia, can moderate indoor temperatures by absorbing heat during the day and releasing it at night, though this might result in warmer indoor conditions during night-time in tropical climates. Conversely, lightweight façade systems such as ACP and low-E glazing heat up and cool down more rapidly, which can enhance indoor comfort if well-insulated [63]. Simulation results from a case study of typical residential buildings in Houston and Phoenix, indicated that age-old constructions are prone to reaching hazardous indoor thermal conditions in heatwave scenarios compared to newer buildings attributed to improved envelope characteristics such as exterior wall insulation, U-value and Solar Heat Gain Co-efficient of windows, roof absorptivity and infiltration rate [82]. Another case study on a 1960s building in Lisbon, Portugal, also highlighted the importance of insulation along with building orientation and occupancy patterns in assessing the vulnerability of occupants to indoor heat exposure [78].

Low-income housing is particularly vulnerable to heat waves due to factors such as poor building quality, inadequate ventilation, and low thermal capacitance. Studies from various regions highlight the challenges faced by low-income communities during heat waves, including elevated indoor temperatures and prolonged discomfort [15, 83]. For example, in Athens, low-income, naturally ventilated houses exhibited considerably elevated indoor temperatures, reaching up to 40 °C, during the extremely hot 2007 summer [15]. Another recent case study in a low-income neighbohood in La Pampa, central Argentina observed inefficiency of houses to effectively handle heat waves [83].

Insufficient ventilation within the buildings significantly contributes to the uncomfortable indoor conditions during heat waves, mainly due to poor naturally ventilated buildings, reliance on passive cooling systems, unaffordability of occupants to air conditioners (AC) and frequent power cuts [64, 80, 83]. Air-driven passively cooled office buildings in Germany is observed to have faced challenges in maintaining thermal comfort during heatwave periods [80]. Simulation findings from a study conducted in Zurich, Switzerland, showed that depending solely on night ventilation is inadequate for sufficiently reducing indoor temperatures during heatwave periods due to UHI [84]. Another simulation study for Barcelona, highlights the fact that, in the coming years, heat waves are expected to diminish the effectiveness of passive cooling methods [64].

However, insulation and ventilation strategies if not appropriately addressed throughout all seasons, can exacerbate indoor living conditions during heat waves. For example, a study on newly constructed and renovated social housing during the 2018 heatwave in the U.K., revealed significantly high levels of thermal discomfort due to insulation and ventilation strategies, which primarily aimed to improve resilience against winter conditions but overlooked extreme heat events [79]. Similarly, the modeling of residential buildings in four representative cold-climate cities in China highlighted the prevalence of overheating issues during hot summers [85]. All these studies highlight the importance of understanding building performance during heat waves and the necessity of building design to ensure effective passive ventilation in conjunction with mechanical cooling systems creating more resilient buildings that can withstand the challenges posed by heat waves. Also, thoughtful insulation measures in buildings need to be ensured for comfort in diverse weather conditions.

The current peak demand of buildings is calculated based on peak load, which can be considered as high-probability events based on previous years' weather data. However, events like extreme heat are generally not considered for peak load calculation because of their low probability. This can lead to a scenario where existing building systems are unable to meet occupants' thermal comfort requirements, even when relying heavily on active cooling systems with increased energy consumption. Widespread usage of AC emerges as one of the crucial factors in reducing heat related mortality and morbidity during heat waves [11, 86–88]. Research conducted worldwide suggests that the global urban burden of additional electricity demand per degree of temperature rise ranges from 0.45 to 12.3% [65]. For each degree of temperature rise, the surge in peak electricity load ranges from 0.45 to 4.6% and an extra electricity penalty of approximately 21 (±10.4) watts per person [65]. Another study that focused on the San Juan Metropolitan Area in Puerto Rico, for a tropical coastal environment highlighted that energy per capita in urban areas could increase by up to 21% during a heatwave event compared to normal days [89]. Building cooling energy consumption during heat waves is influenced by factors such as UHI intensity, building age, degree of insulation and usage of cooling devices by building occupants [13, 90–92]. The estimated additional energy penalty attributed to the UHI phenomenon at the city scale is approximately 70 kilowatt-hours per person per degree Celsius of UHI intensity [13]. The study of four representative office buildings in Vienna, Austria, reveals a notable overall increase in cooling requirements that varies based on different construction periods, and the location within the city, further implying need for a widespread installation of AC [90]. Another numerical investigation of typical Italian residential buildings, during extreme hot periods demonstrated more than threefold increase in cooling requirements of insulated buildings compared to traditional non-insulated buildings [91]. A study focussing on an office building in Zurich during a heatwave indicated that the closed courtyard exhibited a 20% increase, while the open courtyard showed a 9% rise in cooling demand. This attributed to higher air temperatures and lower heat transfer coefficients resulting from reduced local airflow speeds [93]. Recent simulation study conducted in Beijing in the context of global warming and the rising occurrence of extreme heat wave events demonstrated an association of increase of one Cooling Degree Day (CDD) with a growth of 0.053 million kWh in power consumption, further projecting that by 2060, electricity consumption in Beijing will range between 219 and 290.4 billion kWh [94]. All these studies underscore the urgent need to anticipate a potential hike in AC usage and subsequent energy consumption during heat waves in the future.

However, it is also important to note that the escalating demand for AC in buildings can further exacerbate UHI during heat waves, attributed to increased anthropogenic heat generation from indoor electricity systems and the additional heat released by outdoor units of AC. One notable study in Paris for the 2003 heatwave, revealed that the local temperature fluctuations attributed to UHI are directly proportional to the locally released sensible heat by AC systems [95]. In this context, another study in Jiangsu Province, China demonstrated that adjusting the indoor AC target temperature to 25–27 °C could lead to a 12.66% reduction in the total energy release of the AC system [96].

Heat waves, exacerbated by UHI, disproportionately impact multiple urban infrastructure sectors through direct and indirect interconnections. Significant impacts are observed in electricity, healthcare, transport, water distribution systems, and building structures [16, 17]. This causes inconvenience to people by depriving them of basic civic amenities like traffic light failures, traffic congestion, cancellations of train or flight services, water supply shortages, black-out situations, electricity price hikes, etc. Limited studies have evaluated the specific impact outcomes of heatwave events across all sectors and their interconnectedness.

The electricity sector is particularly susceptible to the impacts of synergistic effects of heat waves and UHI, leading to a range of operational challenges and risks [16]. The rise in peak electricity demand affects power generation, transmission networks, and distribution networks [4, 16, 97]. This can result in frequent breakdowns of the system leading to increased frequency of blackout situations [98]. Heat waves pose challenges to power stations by impairing the efficient generation and transmission of power through factors such as diminished insulator capacity and increased breakdown risks [16]. Additionally, nuclear and coal-fired thermal power plants experience operational difficulties mainly due to warming of cooling water during heatwave days, affecting their capacity and efficiency [4]. During the summer of 2009 in France, approximately one-third of nuclear power stations had to be shut down due to cooling water shortages [97]. Moreover, heightened power demand leading to the necessity for extra infrastructure and other operational challenges can escalate prices, particularly impacting lower-income populations who may struggle to afford adequate cooling due to increased costs [4].

The healthcare sector encounters notable difficulties during heat waves, with increased demand for medical services and infrastructure strain. Many epidemiological studies across Europe [99], US [100, 101], Australia [102, 103] and Asia [104] have reported an increase in hospital admissions, emergency department visits, emergency dispatches and ambulance attendances in urban areas, attributed to heat-related mortality and morbidity during heatwave period. The situation can result in overcrowding in hospitals straining available infrastructure related to space, electricity supply, water supply, waste management and critical healthcare services. For example, a recent study forecasts that future heat waves in Phoenix may overwhelm regional emergency departments, as nearly half of the population could require medical care for heat-related illnesses, exceeding the capacity of these facilities [98].

Furthermore, transportation, water resources, and building structural integrity are adversely impacted by elevated temperatures resulting from the combined effects of heat waves and UHI. These high temperatures during heat waves affect road transport by impairing engine and tire performance, increasing air conditioning usage, causing pavement rutting and bridge expansion [16, 105]. Rail infrastructure faces challenges such as track buckling and electrical faults during heat waves [106], while flights may get cancelled due to elevated fuel consumption [105]. Heat waves increase water demand, strain municipal water resources, and elevate the risk of infrastructure damage such as burst pipes and groundwater depletion [17, 105, 107]. Dry weather and high temperatures during heat waves can exacerbate issues like subsidence-related structural damage in buildings, emphasizing the need for further investigation and the application of appropriate construction regulations in subsidence-prone areas. The impacts of heat waves on urban heritage remain largely unexplored [108].

In summary, addressing the complexities of interconnectedness between heat waves, UHI, building performance, increased cooling energy, public health and critical infrastructure requires holistic approaches that encompass urban planning strategies, building design considerations, equitable access to cooling technologies, and community resilience measures. Furthermore, proactive measures to mitigate the impact of heat waves, such as reducing UHI, improving indoor thermal comfort, enhancing ventilation in buildings, and ensuring access to healthcare facilities, are essential to safeguard the health and well-being of urban populations in the face of escalating heat wave risk. By incorporating ecodesign principles, implementing sustainable operational practices, and prioritizing heatwave-resilient maintenance strategies, infrastructure across power, healthcare, transportation, and water sectors can better withstand the challenges posed by heat waves, ultimately enhancing the liveability for urban residents.

Mitigation measures for heat waves in the built environment

This section discusses strategies like GI, BI, high albedo materials, and sustainable building practices that can potentially mitigate high ambient temperatures in building indoors and outdoors, caused by the combined effects of heat waves and UHI, thus aiding in reducing heat wave severity. These strategies are mainly aimed at limiting heat sources and enhancing heat sinks within the built environments [10]. Detailed investigation of various heat wave mitigation strategies to examine their performance and effectiveness mainly gained attraction in the research community in the past decade.

The integration of GI into urban design stands out as one of the most effective measures for mitigating heat waves particularly within the built environments. GI plays a key role in enhancing carbon sinks by sequestering carbon [109, 110], which can mitigate global warming and subsequently reduce the frequency and intensity of heat waves. Moreover, it contributes to moderate the microclimate through processes like evapotranspiration and shading effects [10], thus aiding in UHI mitigation by lowering surface temperatures [111, 112]. Additionally, GI helps improve air quality by reducing urban pollutants

[110]. This multifaceted approach reduces heat-related mortality, lowers peak cooling energy demand in buildings, thereby addressing the combined effects of heat waves and UHI in built environments [113–115]. For example, the reduction in UHI in Shanghai, resulting from an increase in urban green area coverage from 19.1 to 35.2%, is believed to have played a role in the decrease in heat-related mortality during the 2003 heat wave compared to that of 1998 [113]. GI's effectiveness in mitigating the impacts of combined effects of heat waves and UHI in urban areas involves the construction and conservation of green infrastructure elements that significantly improve the cooling effect, mainly through shading and evapotranspiration [10]. This can be done by increasing vegetation within the urban landscape at various levels, including parks, streetscapes, neighborhood open spaces, building roofs, and facades. Table 2, lists the heat wave mitigation potential of various GI and BI strategies demonstrated by studies at different spatial scales.

Urban trees are crucial GI elements particularly in mitigating the effects of hot extremes. Green spaces featuring urban trees demonstrate significantly higher cooling potential, ranging from 2 to 4 times greater compared to treeless green spaces in urban environments depending on their size [54, 114]. However, the cooling impact of GI is influenced by factors such as plant species, time of year, seasonal variations, size and morphology of plants, scale and geometry of the green infrastructure, and the prevailing climate [10, 120]. Recent research findings suggest that during extreme heat waves with very high temperatures, the cooling capacity of transpiration for most plant species is adversely affected [114]. Another study conducting in Munich found that the cooling effect of urban vegetation decreased during the 2003 heat wave, potentially due to vegetation dieback caused by water scarcity, resulting in reduced cooling through shading and evapotranspiration [120]. Thus, long-term irrigation strategies need to be integrated into urban design to improve evapotranspiration in the regions facing groundwater depletion thus reducing heat wave intensity and frequency [114]. Although increasing ground cover with significant trees has a greater cooling effect on street temperatures, green roofs are more effective for reducing energy consumption during heat waves [119, 121]. Integrating green living systems into building envelopes, encompassing horizontal surfaces with green roofs and vertical greening systems for facades is crucial in dense urban areas [109]. GI improves air quality during the heatwave period [122]. However, more urban GI could also increase the emission of biogenic volatile organic compounds (BVOCs), leading to elevated ground-level ozone concentrations, which pose a significant threat to human health [110]. Hence, urban design solutions should seek to maximize mitigation potential from GI strategies by combining them with other heat mitigation measures. In hot and humid urban climates, integrating BI into urban design can improve pedestrian-level thermal conditions by reducing ambient temperatures, energy consumption and enhancing urban ventilation during thermal stress periods [112].

Many studies have demonstrated that widespread implementations of cool and supercool materials with

Table 2 Heat wave mitigation potential of various green infrastructure and blue infrastructure strategies

Location	Strategy	Scale	Mitigation potential	References
Melbourne, Australia	Doubling the city's vegetation coverage	City	Reduction in the heat-related mortality rate ranging from 5 to 28%	[116]
Phoenix, US	Urban vegetation increased by 5, 10, 15, and 20%, respectively	City	Reduction of 17, 35, 53, and 70% in emergency calls related to heat respectively	[84]
Sydney, Australia	Planting of an additional 2 million trees	City	Reduction in peak daily temperature by as much as 1 °C, Reduction in excess heat-related morbidity from 3.7 hospital admissions per day to approximately 2.6 per day per 100,000 inhabitants.	[117]
293 Cities from Alps, British Isles, Eastern Europe, France, Iberian Peninsula, Mediterranean, Scandinavia, Turkey	Urban trees	City	2–4 times cooling potential than tree-less urban green spaces	[114]
Washington DC, US	Additional vegetation	City	Reduction in surface air temperature within urban street canyons by 4.1 K. Reduction in road-surface temperatures by 15.4 K, and building-wall temperatures by 8.9 K during heat wave days.	[111]
Chicago, US	Green roofs	Metropolitan area	Reductions in cooling energy consumption by 14.0%	[118]
Trondheim, Norway	Urban greening	Building	28.5% decrease in cooling energy demand compared to no greenery scenario.	[119]
Karachi, Pakistan	Water bodies on an isolated street	Urban Area	Reduction in ambient air temperature by 0.9 °C and surface temperature by 3.5 °C, improved wind velocity.	[112]

highly reflective properties on roofs and pavements in urban areas can prove to be an effective and affordable technology for combating high ambient temperatures [123]. The highest peak roof temperature reductions achieved by cool and supercool materials are up to 10.7 and 13.4 °C respectively during the summer [124]. These effects can play a crucial role in mitigating UHI, maintaining indoor thermal comfort, lowering cooling energy demands during heat waves, when outdoor temperatures are very high [118, 125–127]. Additionally cool materials help to decrease ozone and PM 2.5 levels [126], thereby maintaining air quality during heat wave periods. Policy interventions to enhance urban albedo at city-scale by utilizing cool pavements, permeable pavements, high albedo roads, cool roofs, and high albedo walls can significantly contribute towards lowering the heat related mortality in cities [127]. As per the information retrieved from Wang et al. [128], California has undertaken various demonstration projects for cool pavements in cities like Chula Vista, Merced, and Sacramento. In 2001, the initial demonstration project of a parking lot at Bannister Park in Fair Oaks marked California's pioneering use of permeable pavements as a strategy to mitigate UHI and heat waves. Table 3, lists the heat wave mitigation potential of high albedo materials and solar panel roof application demonstrated by various studies at different spatial scales.

All these studies endorse increased albedo of roof, walls, roads and pavements in urban areas as an effective mitigation strategy to reduce impacts of combined effect of heat waves and UHI. However, a study in Milan, Italy suggests that the use of high albedo materials requires cautious implementation, particularly during heat wave periods when ambient temperatures are already elevated since high albedo materials have the potential to exacerbate pedestrian thermal discomfort [129]. Deployment of solar panels on rooftops serves a dual purpose of reducing indoor temperatures and conserving energy through renewable sources during heat waves [118].

Literature on recent advancements in material engineering has demonstrated a notable cooling potential of doped reflecting surfaces containing nano PCM and quantum dots, fluorescent materials, thermodynamic materials and daytime radiative cooling, facilitated by photonic materials as they have the ability to attain sub-ambient temperatures, maintaining an average surface that is 5 to 10 °C, lower than that of cooler white materials with a negligible or negative sensible heat release to the atmosphere [21]. Consequently, they can prove valuable in alleviating elevated daytime temperatures, especially during heat wave periods.

Combination of heat mitigation measures in urban design can yield better results in combating impacts of synergies between heat waves and UHI. For example, a study in Darwin, Australia, demonstrated a reduction of 2.7 °C in peak ambient temperature, 2% in peak electricity demand, 7.2% in the total yearly cooling load as well as the potential to prevent 9.66 excess deaths annually per 100,000 people in Darwin district resulting from the combination of cool materials, shading, and greenery [130]. Designing compact, mid-rise buildings with a light-coloured exterior, along with incorporating large parks, green spaces with significant amount of trees in proximity to the buildings could prove to be an optimum urban design solution [122]. These strategies primarily target UHI by reducing heat absorption and promoting cooling, while also contributing to heatwave mitigation through carbon sequestration via vegetation. Additionally, managing building heights to enhance airflow and reduce heat retention within built environments indirectly aids in mitigating heat waves by preventing extreme temperature spikes. While specific studies in humidity-dominated tropical cities emphasize the importance of integrating shading, urban ventilation, vegetation, water bodies, and albedo modifications to lower air

Table 3 Heat wave mitigation potential of high albedo materials and solar panel roof application

Location	Strategy	Scale	Mitigation potential	References
Nanjing, China	Cool and supercool materials on a roof	Neighborhood	Highest peak roof temperature reductions up to 10.7 and 13.4 °C respectively	[124]
Terni, Italy	Increasing albedo	Urban area	UHI mitigation up to 2 °C, peak temperature reduction by 1 °C in the daytime and approximately 2 °Cat night-time.	[125]
Meta-analysis (Baltimore, Los Angeles, New York, New Orleans, Philadelphia, Detroit, Columbia, W Mid. HW, Montreal, Toronto, Darwin, Parramatta, W Mid. NHW)	Increasing albedo	City	Decrease in daily deaths ranging from 0.1 to 4, an average reduction in mortality of approximately 19.8% for each degree of temperature decrease or 1.8% for every 0.1 increase in albedo	[127]
Chicago, US	Cool roofs and solar panel roofs	Metropolitan area	Reductions in cooling energy consumption by 16.6% and 7.6% respectively	[118]
Montreal, Canada	The enhanced albedo of roofs, walls, and roads	City	2% decrease in HVAC energy consumption, decreases in ozone and PM 2.5 levels	[126]

temperatures [131], the underlying principles of these strategies remain applicable across various urban contexts. Adaptations may be necessary to suit the specific climatic conditions and urban landscapes, but the overarching goal of mitigating UHI and heat waves remains consistent.

Furthermore, sustainable building materials and technology can ensure better mitigation effects of heat waves in urban areas. Studies have examined the performance of buildings under various envelope materials and ventilation scenarios when subjected to very high temperatures during the heat wave period [84, 132]. Table 4 lists the heat wave mitigation potential of sustainable building materials and design practices.

The outcomes of studies in Table 4, highlight the effectiveness of utilizing passive envelpe design and ventilation as a promising solution to maintain indoor thermal comfort and safeguard occupants from health risks during heat waves and blackouts [84, 117, 133, 134]. However, studies have also found that passively designed air-driven systems such as night ventilation may get strained during hot extremes necessitating the adoption of advanced natural ventilation strategies or mixed mode ventilation systems alongside appropriate adaptive comfort criteria for heat wave resilience [80, 137]. Additionally, as per [80], water-driven cooling systems utilizing ground cooling outperform air-based alternatives when the levels of outdoor temperatures are high. For low-income housing, adopting building design strategies such as providing shade through elements like trees, climbing plants, green walls, or installing ventilated opaque facades, along with enhancing roofs through light-colored coatings and the addition of thermal insulation, can prove advantageous when combined with night ventilation [83].

Modern buildings need to be designed to optimize glazing areas to curtail intense solar radiation during high ambient temperature days [90]. For buildings where conventional materials like bricks, cement, concrete, and wood, limit envelope cooling potential during heat waves, integrating PCM enhances the sensible thermal energy storage of the building envelope to control indoor temperatures [115, 135, 136]. In conclusion,research progress in applying PCMs in existing buildings (Table 4) offers a viable option for adapting urban building stock to heat waves through convenient and cost-effective retrofit measures.

Many studies have suggested the application of insulating materials for old and new building stock for improved envelop thermal performance during the heat wave period [138]. However improper application of insulation materials without consideration of seasonal variability can have an inverse impact [79]. Also, the external application of insulation materials can add to the surrounding UHI during high ambient temperature conditions [63].

Furthermore, it is essential to consider ecological implications associated with the use of construction materials for combating heat waves. One study in this context has

Table 4 Heat wave mitigation potential of sustainable building materials and design practices

Location	Strategy	Scale	Mitigation potential	References
California, US	High thermal mass envelopes in conjunction with night ventilation	Building	Indoor maximum temperatures maintained up to 24 °C were well within the comfort zone limit on heat wave day.	[133]
Zurich, Switzerland	Precooling ahead of a heat wave and desorption cooling from hygroscopic materials	Building	Reduction of 1.31 °C in the average operative temperature during the heat wave period.	[84]
Cordoba, Spain	Courtyard layouts incorporating passive shading, monitoring	Building	Temperatures up to 8.4 °C lower than the external environment, thermal comfort for an average of 52 to 73% of the time during heat wave periods	[117]
Seville, Spain	Roofs, wall insulation combined with night natural ventilation	Building	Extension in the duration of thermal comfort hours during heat waves, ranging from 2 to 5 times longer compared to inadequately insulated buildings.	[134]
Al Hoceima (Morocco), Malaga (Spain), Marseille (France), Taher (Algeria), Naples (Italy), Tripoli (Libya), Ankara (Turkey), and Port Said (Egypt).	PCM with hollow brick walls	City	Energy savings of up to 56%	[135]
Lucknow, India	Latent heat storage brick	Building	Average peak temperature reduction of 3.86% in comparison to conventional brick and time lag of 180 min	[136]
Melbourne, Australia	Aerogel render and PCM on external walls and insulation in ceilings	Building	Reduced severe discomfort hours by 82% in a free-running building, 40% in energy use, 65% in peak cooling demand, 64% in CO_2 emissions, and 35% in operational energy costs for air-conditioned setting.	[115]

demonstrated that the lightweight Autoclaved Aerated Concrete with the optimal sugar sediment content could effectively delay the propagation of heat waves from the outer wall to the inner wall [139], thus exhibiting the ecological, financial, and health implications associated with diverting a significant volume of industrial waste from landfills.

The review of existing literature underscores diverse approaches to mitigate the impacts of combined effects of heat waves and UHI in built environments. While many strategies primarily target UHI rather than directly addressing heat waves, it's essential to recognize their distinct contributions in mitigating both phenomena. This understanding helps in better responding to the synergies between heat waves and UHI. Heat mitigation approaches span across various spatial scales, from city-wide initiatives to neighborhood-level interventions and building-specific measures. Key findings emphasize the importance of tailored solutions at the urban design level, incorporating a combination of urban trees, blue infrastructure, and high albedo materials to effectively mitigate heat during heat waves. At the building design scale, advanced mixed-mode ventilation systems and emerging technologies like PCMs offer promise in enhancing building thermal performance. Challenges identified include cautious implementation of high albedo materials and ecological implications of construction materials. Future research should optimize synergies among mitigation measures across various spatial scales such as city, neighborhood and buildings to address effectiveness across urban contexts, and prioritize ecological sustainability. Building regulations need to integrate region-specific adaptive criteria specifically for mixed mode ventilation systems, while careful development of energy benchmarking policies is essential to manage increased cooling demands. Policy responses need to consider population dynamics, temperature shifts, and economic factors, urging tailored strategies for each city. Future research needs to focus on aligning regulations and policies with both environmental and societal needs to foster sustainable urban development amidst heat wave challenges.

Case studies and best practices

Cities around the world have implemented various successful heat wave and UHI mitigation strategies to address the challenges posed by rising temperatures. Existing literature on these case study examples highlights valuable insights regarding success as well as challenges at the implementation level. For example, Chicago and Melbourne have extensively implemented green roofs, tree-planting initiatives, and increased green spaces to combat UHI [22, 140]. In response to the 1995 heat wave and increasing urban heat challenges, Chicago implemented various green infrastructure interventions, including incentivizing vegetated roofs and mandating reflective roof implementation on new buildings through zoning requirements [22]. The Green Alley initiative in Chicago, Illinois utilized a range of strategies to mitigate UHI. This included the implementation of cool pavements and green roofs. Over the period from 2001 to 2017, more than 300 Green Alleys were established as part of this initiative [128]. Melbourne, Australia, exemplifies successful heat mitigation through urban greening initiatives characterized by effective governance. These initiatives operate on diverse scales and involve collaborative efforts from various stakeholders from administrators, policymakers, and urban planners to non-governmental organizations, community groups, and private landowners [140]. The Urban Forest Strategy implemented by Melbourne's central city municipality serves as an exemplary case study in mitigating climate change impacts induced by heat waves and UHI through urban greening initiatives. This strategy demonstrates the importance of informed decision-making and collaborative co-creation in addressing these climate challenges [141]. These measures often lead to temperature reductions and improved microclimates. However, critical evaluations should delve into the long-term viability as well as their equitable distribution across diverse urban landscapes. However, a comprehensive review should assess the environmental consequences of such technologies and their adaptability to different urban settings. It's crucial to examine the durability of cool pavements and their effectiveness over extended periods.

Similarly, there is significant experimentation taking place in the development of innovative architectural designs and technologies aimed at mitigating the impacts of combined effect of heat waves and UHI. A critical review of selected designs and technologies underscores both their merits and the need for careful consideration of their application. Daramu House, constructed in 2019 in Barangaroo, Sydney, Australia, boasts a green roof with around 15,000 native plants and PV panel coverage. It showcased notable reductions in rooftop surface temperatures, up to 20 °C during ambient temperatures over 40 °C, and improved heat flow efficiency by up to 55.54% compared to conventional buildings lacking green roofs [142]. In a Hong Kong study, turf-based vegetation cladding on an elevated facade wall of a public housing apartment demonstrated a notable reduction in interior temperatures and delayed solar heat transfer leading to lower air-conditioning power consumption compared to a building with exposed concrete. However, the study emphasizes the crucial role of maintaining a healthy plant cover and a supportive substrate, as the cooling effect through transpiration relies on their robust presence sustained by proper irrigation practices [143]. Bosco Verticale in Milan, the "vertical forest" that incorporates over 13,000 plants across 90+species, including full-sized trees, on its towers' facades, showcases innovative engineering for cultivating trees on high-rise balconies, serving as a model for urban greening to mitigate impacts of higher temperatures during heat waves [144]. However, successful implementation of such innovative technologies requires collaboration among experts in architecture, structural engineering, botany and climatology to address issues like adapting to altered growing conditions, tree stability, irregular growth, planting restraint safety systems and regular maintenance. The combination of multiple passive strategies in buildings based on the local climatic conditions can be an innovative architectural design approach to reduce building energy consumption and thereby mitigate heat wave impacts on the energy sector. The Pearl River Tower in Guangzhou employs a double-skin facade with integrated wind turbines and solar panels. The facade design allows for natural ventilation and passive cooling, utilizing wind pressure differences between the outer and inner layers [145]. Traditional passive ventilation concepts equipped with modern technologies prove to save significant amounts of energy in buildings providing promising solutions to electricity breakdown situations during heat waves. For example, as mentioned by Saadatian et al. [23], Council House 2 (CH2), Melbourne, Australia utilizes advanced wind catcher technology with five installations on its southern façade connected to the basement tanks filled with phase-change material balls that freeze at 15 °C, providing efficient cooling for circulating water through convection thereby achieving 80% reduction in energy consumption. However, the system's effectiveness could be influenced by changes in wind patterns and solar exposure, posing challenges in maintaining consistent energy efficiency across different seasons and weather conditions. Also, addressing potential challenges of initial costs, appearance concerns, etc. is essential for the long-term success and widespread adoption of similar designs in the future.

While case studies and innovative practices provide valuable insights into successful urban heat mitigation strategies to lower the impacts of heat waves and UHI, they should be critically reviewed for longevity, scalability, and equity considerations. The interconnected nature of climate challenges demands a nuanced understanding of the social, economic, and environmental implications of each strategy to inform future urban planning and heat mitigation efforts.

Future prospects and challenges

The future impact of climate change on heat waves and urban areas is a critical concern that demands careful examination to develop effective mitigation and adaptation measures. Outcomes of several studies have projected a significant increase in days, frequency and duration of heat waves by the end of the century [1, 2]. The synergetic impact of UHI and heat waves is predicted to pose significant challenges towards increased health risks, elevated energy demand for cooling systems, and strain on urban infrastructure due to overheating in cities. Many research studies have explored the correlation between anticipated future temperature rises and corresponding levels of heat related mortality under climate change scenario [146]. For example, Examination of 144 articles focused on assessing the influence of climate change on the prospective energy consumption of commercial buildings across 40 cities for the timeframe spanning 2030–2100, and considering temperature increases in the range of 0.4–5 °C, has revealed that the anticipated rise in cooling demand varies from 1 to 86 kWh/m^2/year. This variation is influenced by factors such as future climatic scenarios, existing climatic conditions, and specific building characteristics [147]. The research gaps identified in the existing knowledge and methods that need to be addressed in the context of impacts of synergistic relationship between heat waves and UHI on built environments have been listed below. However, the list is not exhaustive.

- Heat vulnerability index (HVI) and related thresholds often fail to integrate demographic, socioeconomic and climatic attributes with physical building attributes. Additionally, indoor heat wave thresholds need to be developed with occupant-centric approaches that consider personal factors, adaptive comfort and behavioural patterns.
- There is a need to gain a more comprehensive understanding of the capabilities of the current building stock with a consideration of a wider array of samples to encompass various construction typologies and ventilation scenarios in varying climatic and urban settings.
- The resilience of low-income group populations to heat waves, particularly in relation to mitigation strategies within the built environment, is still an important area to be investigated.
- Research on the impacts of heat waves on heritage areas needs to be explored further to comprehensively understand this aspect.
- Future research needs to focus on building energy optimization and promising solutions to combat heat wave impacts that combine passive and active systems.
- There is also an urgent need to consider the impact of increased anthropogenic heat generation from indoor electricity systems during extreme hot events on the outdoor thermal environment.

- The gap between recent scientific advancements in material technologies exhibiting high heat mitigation capabilities and their application in buildings needs to be bridged.
- Future research exploring nature-based solutions should holistically consider challenges such as initial capital requirements and the absence of comprehensive policies.
- Researchers should consider effective water management for the irrigation of GI during heat waves to enhance cooling effects, particularly in anticipation of future challenges related to water scarcity and groundwater depletion in urban areas.
- Studies on mitigation measures should consider variations in local UHI and moisture fluxes at various spatial scales.
- The critical role of community resilience and social equity in urban planning and infrastructure development to mitigate the impacts of heat waves requires greater attention.

The utilization of advanced technologies in future studies could play a pivotal role in addressing the challenges posed by the impact of climate change on heat waves and the built environment. For example, Space-based Earth observation for the long-term monitoring and quantification of gradual changes in the climate system resulting from the accumulation of greenhouse gases in the atmosphere and the subsequent rise in surface temperatures [148]. This technological approach will be useful in tracking slow environmental shifts and also for assessing progress and accomplishments regarding implemented policies toward heat wave mitigation and adaptation. Furthermore, this will reduce inconsistencies in varying database approaches used for climate monitoring across varied disciplines. Design actions aided by an Environmental data-driven design process is an innovative approach that combines environmental and technological design processes. Leveraging Information and Adaptive Communication Technologies tools for simulating the built environment through an environmentally data-driven approach ensures data interoperability between outdoor and indoor environments [149]. Progress in urban climate modeling involves coupling a meteorological model with a building-resolved local urban climate model and linking an urban climate model with a building energy simulation model [93]. This integrated methodology facilitates not only the design of buildings tailored to the local climate but also allows for a comprehensive understanding of the intricate interactions within the urban environment. Advancements in prediction modeling techniques forecasting vulnerability of urban areas, temperature rise, building energy demand and electricity demand can play a crucial role in informed decision-making and infrastructure preparedness for heat wave adaptation in urban areas [94, 150].

Integrating community resilience and social equity into mitigation efforts at the local level to address the synergistic impacts of heat waves and UHI poses a considerable challenge. For example, a study in Winnipeg, Canada, revealed notable discrepancies between public and expert perceptions of heat waves and related risks, highlighting misconceptions about climate change effects and policy intervention responsibility. This underscores the imperative for enhanced risk communication tools and increased public engagement in knowledge-building practices [151]. Transitioning from national-level to municipal-level plans is crucial to facilitate localized actions toward community resilience in mitigating future heatwave events [152, 153]. Local level initiatives to enhance community resilience can offer co-benefits for mitigating heat wave impacts in urban areas. For example, planting trees for shade, implementing cool roof programs, and adopting energy-efficient building designs help lower surface temperatures, reduce cooling energy demand, thereby mitigating UHI and reducing the severity of heat waves. Additionally, rectifying disparities and ensuring equitable access to cooling resources, green spaces, and protective infrastructure for vulnerable populations within the urban planning and infrastructure development processes can facilitate effective heat mitigation during heat waves.

Conclusion

Over the past three decades, scientific advancements have significantly enhanced our understanding of heatwave thresholds, characteristics, and their intricate relationship with UHI, particularly concerning land use, urban planning implications, and mitigation strategies. The convergence of UHI and heat waves amplifies ambient temperatures, leading to urban overheating, with densely urbanized areas bearing the brunt due to high pollution levels and heat-retaining building materials. Notably, low-income groups face heightened risks during heat waves, exacerbated by limited access to cooling, healthcare, and poorly constructed homes, underscoring the urgent need for policies addressing heat mitigation in urban and building design. Key findings from past studies emphasize several crucial points for reducing heatwave impacts in cities:

- Integrating innovative green and blue infrastructure solutions into urban planning, addressing challenges such as the cooling capacity of plant species and water availability constraints.
- Introducing a blend of compact, mid-rise structures featuring light-coloured facades, in conjunction with

expansive parklands, to effectively mitigate rising air temperatures.
- Harnessing cutting-edge cool and supercool materials, alongside sustainable architectural designs, to bolster heat mitigation efforts.
- Enforcing stringent building regulations promoting energy optimization, especially during periods of heightened heat waves, while incorporating region-specific adaptive comfort standards.
- Deploying advanced passive cooling and ventilation systems tailored to alleviate vulnerabilities in economically disadvantaged households.
- Formulating robust policies and action plans emphasizing community engagement and equitable social participation to strengthen mitigation efforts against combined effects of heat waves and UHI.
- Fostering seamless alignment between national-level action plans and localized urban planning strategies to enhance overall effectiveness in mitigating heat-related risks.

The review underscores the intricate relationship between heat waves and the urban built environment, highlighting the need for ongoing scientific innovation through interdisciplinary collaboration. By embracing diverse approaches, stakeholders can devise comprehensive strategies to mitigate heatwave impacts in urban areas while promoting sustainable development. Integration of expertise from architecture, urban design, environmental science, public health, and social sciences in urban planning is essential to prioritize heat mitigation and enhance community resilience against the compounded challenges posed by heat waves and UHI through tailored micro built environment designs. Collective efforts involving government, academia, non-profit organizations, and industry sectors drive innovation in resilient infrastructure, urban greening, and public health interventions. Empowering communities through inclusive decision-making strengthens their capacity to implement measures aimed at mitigating the negative consequences resulting from the synergies between heat waves and UHI.

Future research directions should focus on refining city-specific heatwave definitions, establishing occupant-centric thresholds, and exploring local moisture variations. Additionally, optimizing building geometry and thermal characteristics for both existing and new structures is imperative. A holistic understanding, with reduced uncertainties in predictions, can be achieved by developing integrated future scenarios that consider impacts and mitigation efforts across various scales. This entails examining future developments and interconnections between global, regional and local climate dynamics, socio-economic factors, demographics, and technological advancements to comprehensively assess the vulnerability and impacts of heat waves and UHI on health, energy consumption, and the environment.

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Competing interests

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