



Sustainable urban mitigation strategies regarding heat-related mortalities and thermal discomfort: an overview and comparative analysis

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Abstract

This study provides an overview and comparative analysis of sustainable urban mitigation strategies to address heat-related mortalities and thermal discomfort. Employing a comprehensive literature review and quantitative analysis, it evaluates various interventions—including green infrastructure, building materials, urban morphology, and technological innovations—alongside their impacts on mortality rates. A novel methodology is proposed for assessing the relationship between urban design factors and heat stress-related health outcomes, with attention to vulnerable populations. Key findings reveal that each 0.1 increase in normalized difference vegetation index (NDVI) reduces heat-related mortality by 6–10% in low-GDP regions, while medical strategies such as warning systems and cooling centers lower mortality by 10–30%. However, emerging technologies like PV panels and AAHPs show localized temperature increases of up to 0.9°C. This paper highlights the critical role of balanced urban strategies to mitigate adverse effects of climate change, offering practical insights for policymakers, urban planners, and public health officials seeking sustainable solutions.

Keywords Urban heat island (UHI) · Heat-related mortality · Heat-wave · Climate change · Mitigation strategies · Representative concentration pathways (RCPs) · Public health · Urban energy planning

1 Introduction

Urban morphology, building design, and material choices are pivotal in mitigating heat-related health impacts, aligning with the goal of creating sustainable urban environments. This paper aims to deal with how to mitigate climate change heat-related health impacts with sustainable urban strategies. Achieving this goal required an examination of recent studies, evaluating the effectiveness of strategies, and highlighting the potential of each strategy needing improvement or

be highlighted. A review involving a thorough analysis and evaluation of existing literature was carried out, which identified significant gaps and potential policies. Then, a series of acceptable strategies have been analyzed numerically to show the potential of each strategy on UHI and heat-related mortalities among different human groups and climates.

This paper investigates sustainable urban development strategies to mitigate heat-related mortalities, with a particular focus on the OTC indexes. The study examines recent literature and employs quantitative analysis to evaluate the effectiveness of various urban strategies. This comprehensive review aims to highlight the theoretical progression and meaningful thematic connections between different research streams. The primary objective of this study is to propose a novel methodology for assessing the impact of these strategies on mortality rates, particularly in the context of urban heat islands (UHIs) and climate change. By synthesizing findings from diverse studies, this paper aims to provide a cohesive framework for understanding the complex interactions between urban planning, public health, and environmental sustainability.

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Theoretical framework The theoretical framework for this study is based on the following key components:

- **Urban Heat Island (UHI) Effect:** Understanding the causes, impacts, and mitigation strategies of UHIs.
- **Heat-Related Mortality:** Examining the factors contributing to heat-related mortalities and identifying vulnerable populations.
- **Thermal Comfort Indices (TCI):** Evaluating various thermal comfort indices and their applicability in urban planning.
- **Sustainable Urban Strategies (SUS):** Assessing the effectiveness of sustainable urban strategies, including green infrastructure (GI), reflective materials (RMs), and technological interventions (TI).

By establishing this framework, the paper aims to create a meaningful analysis of the interaction of different research streams and provide a comprehensive understanding of the subject matter.

This paper emphasizes Europe because this region has been at the forefront of urban heat adaptation studies, providing rich datasets and pioneering approaches to mitigate the impacts of climate change, providing a solid foundation for the study. Europe's diverse climatic zones and urban morphologies provide valuable insights into effective mitigation measures. However, to ensure a global perspective, this study integrates examples and data from regions such as Asia, Africa, and North America, where extreme heat events and urban heat island effects are increasingly prominent challenges. For instance, Chinese cities like Beijing and Chengdu face significant heat stress challenges due to relative humidity, while American cities such as Atlanta and Phoenix implement cooling centers and public education campaigns to combat extreme heat. This broader inclusion

demonstrates the adaptability of mitigation strategies to diverse contexts, emphasizing the universal relevance of findings presented in this paper.

Extreme heat poses a significant threat, resulting in fatalities and causing substantial disruptions to health, security, well-being, infrastructures, and economies (Fig. 1) (Guterres 2024; Failed 2024a; Johnson et al. 2024). In 2022, Europe experienced its hottest summer on record (Beck et al. 2022), followed by 2023, which became the hottest year ever documented. Notably, July 2023 set the record as the hottest month ever recorded, with July 6, 2023, marking the hottest single day in history. Remarkably, each of the past 12 months has consecutively broken previous monthly temperature records. These unprecedented trends are not random or coincidental; their causes are well-documented, and their impacts are profoundly devastating ([Online]. Available 2024).

The way human actions contribute to the driving forces of climate change and the consequent effects on human well-being are discussed from an Earth systems perspective, stressing the importance of addressing data gaps to prevent overly simplistic models (Johnson et al. 2024). The model noted the heightened awareness of climate change due to record-breaking temperatures and their effects, which have led to significant economic losses from extreme heat and El Niño events. This model introduced a framework illustrating how climate change triggers changes that impact human health, and well-being, creating a feedback loop within the climate system (Fig. 1). It emphasizes the necessity of incorporating human factors into climate models to better grasp and manage climate risks, while also recognizing the difficulties in reconciling various scales and uncertainties in these models (Johnson et al. 2024).

Recent findings from the International Labor Organization (ILO) indicate that over 70% of the global workforce, equating to 2.4 billion people, is at significant risk

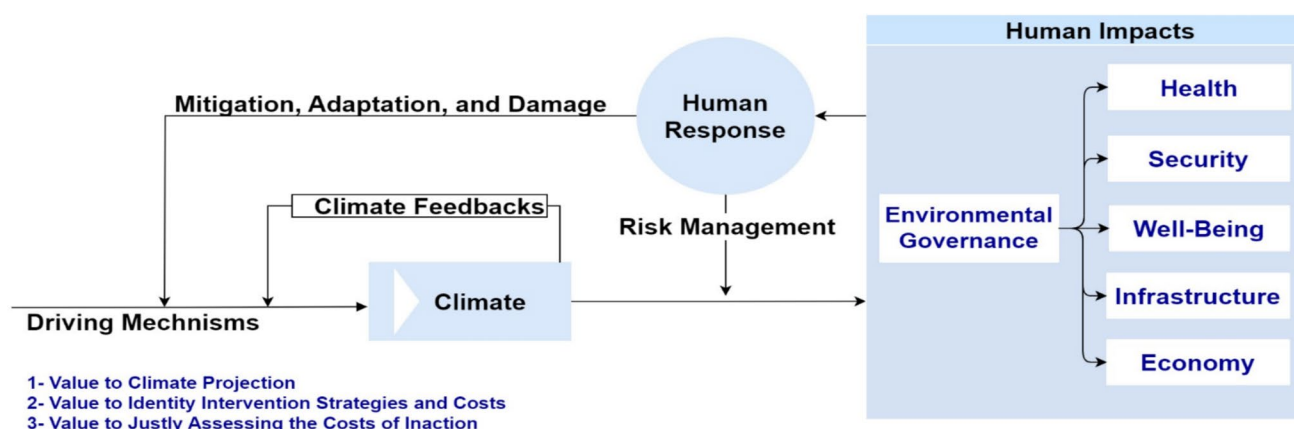


Fig. 1 An endogenous framework illustrating the way human actions contribute to the driving forces of climate change and the consequent effects on human well-being. Adapted from (Johnson et al. 2024)

of health hazards due to extreme heat. This exposure is responsible for approximately 22.85 million injuries and 18,970 worker fatalities annually. The highest risk is in regions such as Africa, the Arab states, and Asia and the Asia–Pacific, where 93%, 84%, and 75% of the workforce, respectively, are impacted. Furthermore, when daily temperatures exceed 34 °C, labor productivity can decrease by 50% (Failed 2024a).

Climate change, driven primarily by anthropogenic greenhouse gas emissions, poses an alarming threat to global public health (Caldeira, et al. 2023). These changes in the Earth's climate are manifesting through an increase in the frequency, intensity, and duration of extreme weather events, such as heat waves, which can lead to substantial increases in morbidity and mortality (Basu and Samet 2002; Pal and Eltahir 2016; Fouillet 2003). Understanding the complex and multifaceted impacts of climate change on human health is crucial for developing effective mitigation and adaptation strategies.

The health consequences of climate change are diverse and far-reaching, affecting respiratory, cardiovascular, and other systems, altering the incidence and geographic distribution of infectious diseases, and even impacting mental health (Caldeira, et al. 2023; Basu and Samet 2002; Pal and Eltahir 2016). Importantly, the burden of these impacts is disproportionately borne by vulnerable populations, including the elderly, young, disabled, and those living in poverty (Pal and Eltahir 2016; Deaths 2023). Addressing these disparities is essential for ensuring equitable and just climate change adaptation.

While climate change mitigation strategies, such as reducing greenhouse gas emissions, are crucial, the persistent increase in emissions necessitates the development and implementation of robust adaptation measures (Robine, et al. 2003; Gamble et al. 2013; Alahmad 2023). Engineering solutions, including renewable energy generation, improved energy efficiency, bioclimatic architecture, urban planning, and resilient infrastructure, can play a pivotal role in enhancing societal resilience and reducing the negative impacts of climate change on human health and the environment (Carleton 2022; Bresch and Aznar-Siguan 2021; Scovronick 2017). However, these emerging technologies should be adapted appropriately to the location conditions to prevent intensifying the mesoscale UHIs (Höhne, et al. 2021).

By integrating climate considerations into policy and urban strategies, the results can catalyze robust urban development while also reducing vulnerability to climate change (Höhne, et al. 2021). This approach is not only about coping with and managing the impacts of climate change but also about preventing those impacts from growing worse, especially the adaptation of emerging technologies. Ultimately, the goal is to build a climate-resilient society that is

safe, healthy, and equipped to deal with the challenges of a warmer world.

The decrease in mortality rates due to increased NDVI and orientation techniques aligns with the theoretical framework's emphasis on green infrastructure as a critical element in sustainable urban strategies, highlighting its contribution to improved outdoor thermal comfort indices (Ouria 2017; Ouria et al. 2018, 2017). Effective health strategies such as cooling centers and heat-health warning systems are essential components of sustainable urban strategies, as outlined in the theoretical framework. These measures directly address the vulnerability of populations exposed to heat-related mortalities.

The scientific literature examined in this paper provided crucial insights into the complex interactions between climate change, human health, and the built environment. The findings lead to the development of evidence-based policies, targeted interventions, and innovative engineering solutions to address the public health challenges posed by a changing climate. This paper proposes a novel method to understand the potential of each strategy on raising and/or decreasing mortalities that serves as a resource for researchers, policymakers, and practitioners working towards more sustainable urban planning.

2 Research methodology

The literature review encompasses studies published between 2000 and 2025, focusing on recent advancements in urban heat island mitigation strategies and heat-related mortality. The inclusion criteria for the literature review were as follows:

- Peer-reviewed articles published in English, Portuguese, Turkish, and Persian.
- Studies focusing on urban heat island effects, heat-related mortality, and thermal comfort indices.
- Research was conducted in diverse geographic regions, including Asia, Europe, and America.

The literature search was conducted using the Web of Science and Scopus databases and Google Scholar, yielding a total of 450 articles. After screening and removing duplicates, 245 unique papers were selected for detailed analysis. Finally, this paper used 187 different sources (Table 1).

Answering how to mitigate heat-related mortality by urban strategies requires addressing several sub-questions:

- What are the effective indexes on OTC?

Table 1 The RCP scenarios

RCP	Radiative Forcing (W/m ²)	Estimated Temperature Increase (°C)	CO ₂ Concentration (ppm)	Target Year
RCP 2.6	2.6	1.5	421	2030
RCP 4.5	4.5	2.4	538	2050
RCP 6.0	6.0	3.0	670	2070
RCP 8.5	8.5	4.3	936	2100

- How do Urban Heat Islands (UHIs) impact heat-related mortalities?
- Which strategies should be effectively adopted to mitigate UHI?
- Which human groups are more vulnerable in different climates?
- Which strategies work well with different human groups?
- Do emerging renewable-based technologies mitigate UHIs?

To answer the research questions, a review of existing literature was undertaken, focusing on the keywords “heat-related mortality”, “outdoor thermal comfort indices,” “UHI mitigation”, “Representative Concentration Pathways (RCPs)”, “NDVI”, “greenery” “NDBI”, “SVF”, “H/W”,

“EVs”, “PCM”, “morphology”, “albedo”, “PV”, “electrification”, “decarbonization”, and “urban health” within the Web of Science and Scopus databases. Initially, 150 articles were retrieved from the Web of Science core collection, 220 from Scopus, and 30 sources through other methods totaling 450 articles. These sources were then meticulously screened and aligned, with duplicates removed, resulting in 245 unique papers. Subsequent screening of titles, abstracts, and methodologies eliminated irrelevant papers, culminating in 105 high-quality sources.

Table 22 shows the distribution of study types, revealing that reviewing and assessment studies constitute the majority of studies. The literature review underscores the increasing scholarly attention to mortality and its implications for urban health and UHI mitigation.

Building upon the insights gained from the comprehensive review of existing literature, this section delves into the research methodology employed to systematically address the key questions identified. The reviewed studies have highlighted significant gaps in current knowledge, particularly regarding the integration of sustainable urban strategies and their quantifiable impacts on heat-related mortality. Consequently, the methodological framework is designed to fill these gaps by leveraging both qualitative and quantitative approaches, ensuring a robust analysis of urban heat mitigation strategies across diverse climates and populations.

Table 2 Distribution of Studies by Methodology Types

Methodology	Areas	No
Reviews	Scoping, critical, meta-analysis	Systematic Review of UHI, Systematic Review & Meta-Analysis of mortality, State of the Science Review, Medical Review, Literature Review, Review, UHI Review, Comparative Review, Perspective 28
Case Studies	Urban/OTC/Energy/Economic/Spatial/Temporal	EVs Case Study, Urban Climate Assessment, Renewable Energy Assessment, Solar Energy Assessment, Decision-Making Study, Economic Assessment Spatiotemporal Study, Spatial and Temporal Study, Spatial Analysis, Multi-temporal Analysis, Seasonal Study 28
Assessments	Epidemiological, Projections	Climate Projection Study, Climate Impact Assessment, Health Impact Assessment, Risk Assessment, Impact Assessment, Economic Assessment 10
Quantitative	Quantitative/Research/Index/Numerical	Quantitative Study, Quantitative Investigation, Original Research, Modeling Study, Analytical and Numerical Study, Analytical Study, Empirical Study, Index Development Study, Numerical Study 6
Online Resources	Online Resources	Online Resource 8
Machine Learning/Algorithm	Machine Learning/Simulation/Algorithm	Machine Learning Study, Satellite Image Analysis, and Image Processing 4
Qualitative Studies	Non-numerical	Urban, management, planning, architectural 97
Perspective Articles	Theoretical Studies	Strategies, theories 6

3 Literature review

3.1 Representative concentration pathways (RCPs) in literature

The Representative Concentration Pathways (RCPs) constitute a series of climate change projections designed to forecast future concentrations of greenhouse gases and their resultant climatic effects. Endorsed by the Intergovernmental Panel on Climate Change (IPCC), these scenarios delineate varying trajectories of radiative forcing values anticipated by the year 2100, with values ranging between 2.6 and 8.5 W/m² (refer to Table 2), (D. P. 2011; Riahi, et al. 2011; Burgess et al. 2023).

These scenarios are indispensable for climate modeling, facilitating policymakers' comprehension of potential future climate conditions and the requisite mitigation efforts. As indicated by Autio *n.d.* and (Ritchie *n.d.*), in Fig. 2, positive values of relative changes estimation in mortality rates denote an increase in mortality rates, while negative values signify a decrease. Premature deaths, measured per 100,000 individuals, include fatalities resulting from both extreme heat and cold temperatures. The RCP 2.6 scenario aims to constrain global temperature rise to below 1.5 °C by the year 2100, corresponding to a radiative forcing level of approximately 2.6 W/m² (D. P. 2011). Considering the extensive time and effort required to analyze data from all 732 locations, our focus will be mostly on EU countries exhibiting high mortality rates related to heat and cold attributed to climate change (Autio *n.d.*). The RCP 4.5 scenario forecasts approximately 2 °C of warming by mid-century and 2.5 °C

by 2050. Under the RCP 6 scenario, greenhouse gas emissions are projected to peak around 2080 before declining, resulting in a radiative forcing of about 6 W/m² by 2100. The RCP 8.5 scenario anticipates a continuous rise in greenhouse gas emissions throughout the twenty-first century, leading to a radiative forcing of approximately 8.5 W/m² by 2100 (D. P. 2011; Ritchie *n.d.*). The projected changes in mortality rates due to non-optimal temperatures across different regions by 2100 under this scenario are as follows.

Positive values signify an increase in mortality rates, while negative values indicate a decrease. Premature mortality encompasses deaths attributable to both extreme hot and cold temperatures, which are quantified per 100,000 individuals. These estimates are derived from the Representative Concentration Pathway (RCP) 4.5 scenario, which projects approximately 2 °C of global warming by the mid-twenty-first century and 2.5 °C by the year 2100 (D. P. 2011; Ritchie *n.d.*).

In absolute terms, these changes can be substantial. For instance, in India, heat-related deaths could increase by 6 per 100,000 people, equating to an additional 100,000 deaths annually by 2050 (Ritchie *n.d.*). Various studies on future heat-related mortality exhibit consistent global patterns, although results may vary. For example, research across 451 locations in 23 countries under different climate scenarios found a decrease in heat-related deaths in North America, Northern Europe, East Asia, and Central America, but an increase in Southern Europe, Eastern Asia, and Central-South America, particularly in the latter half of the century (Fig. 3).

The analysis consistently indicates that variations in heat-related mortality highlight significant disparities between

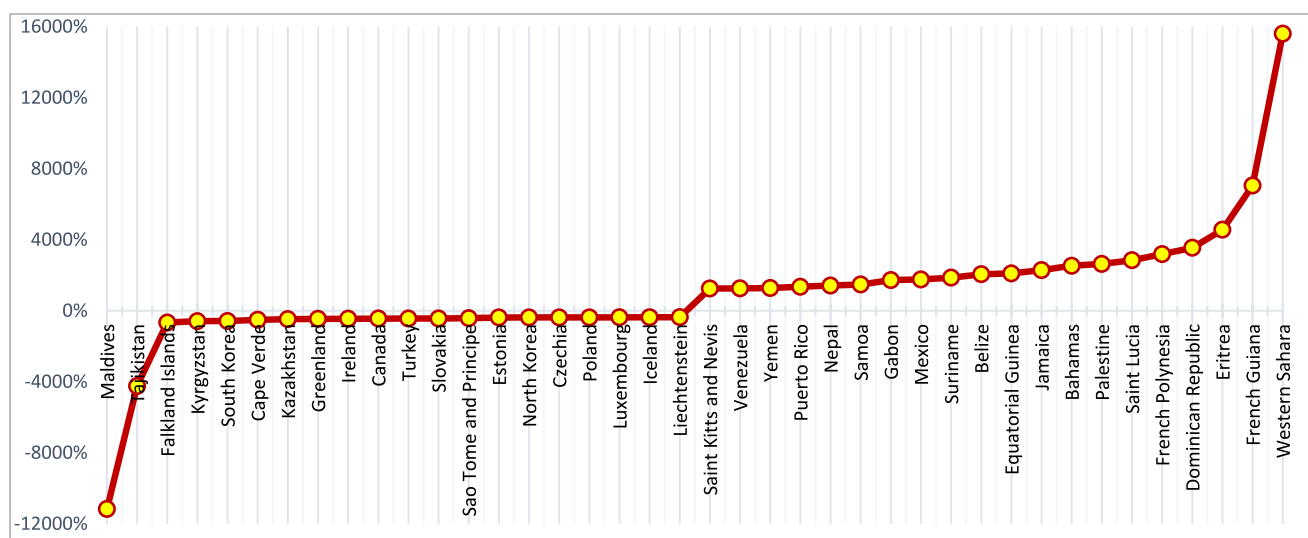


Fig. 2 Relative changes estimation in mortality rates from non-optimal temperatures under 2 °C scenario (2030–2090) adopted from (D. P. 2011; Autio *n.d.*; Ritchie *n.d.*)

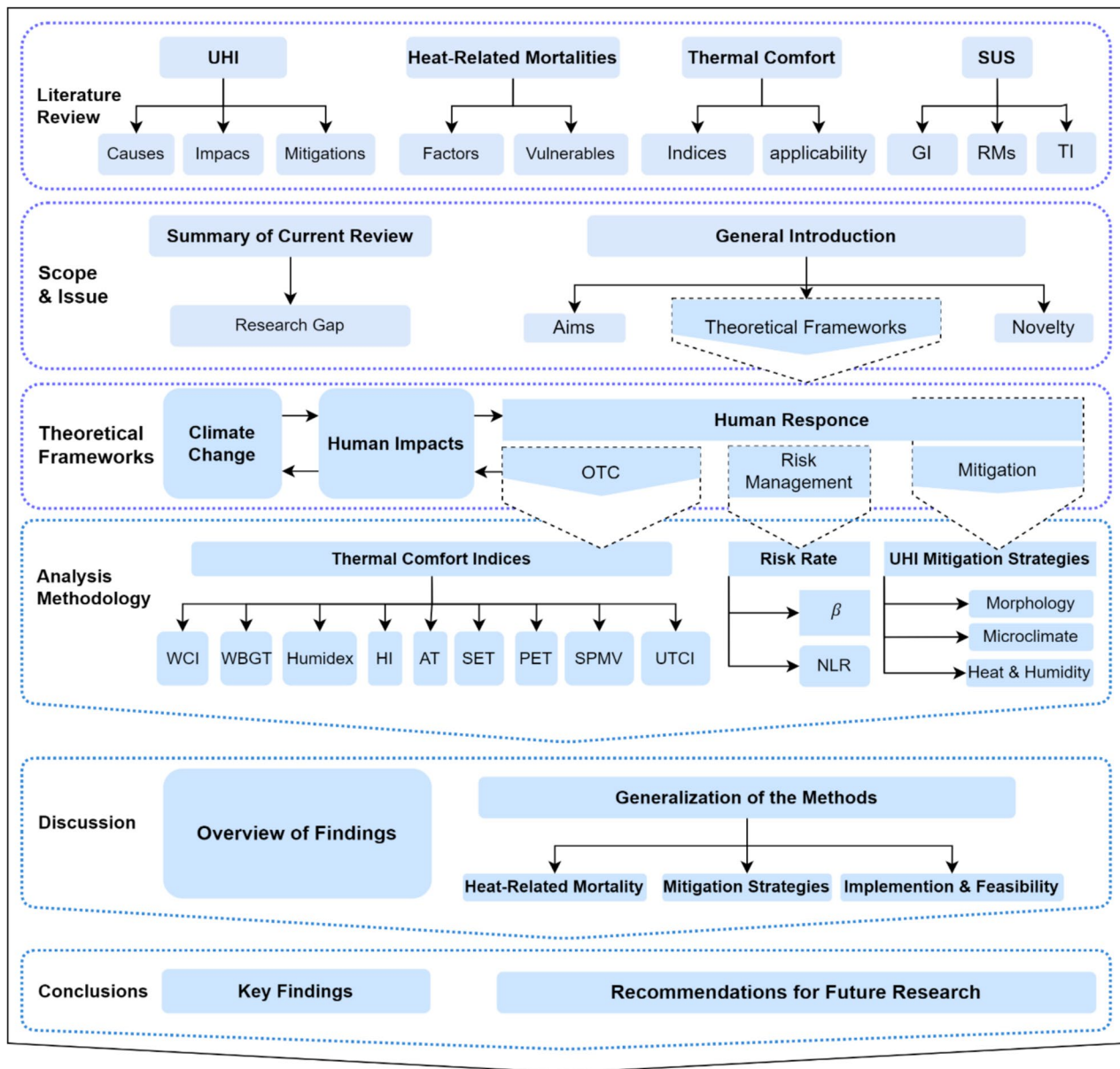


Fig. 3 Research Methodology Process

those primarily responsible for climate change and those most affected by its impacts. In wealthier nations, particularly in Europe and North America, the number of deaths due to climate change is expected to decrease. Conversely, mortality rates in many poorer countries are likely to rise, although these projections are subject to considerable uncertainty due to the complexities of modeling factors such as mitigation and adaptation (Fig. 4).

This stark inequality underscores the broader issue of climate change. The disparity is evident when examining the projected changes in death rates by 2050 relative to the

current gross domestic product (GDP) per capita. The data suggest that death rates will increase in many of the world's poorest countries and decrease in most affluent countries.

3.2 Heat-related mortality in Europe

Ongoing research endeavors aim to quantify the health effects of climate change, encompassing both current and projected impacts. While the following studies include data from multiple countries, they provide valuable insights relevant to Europe.

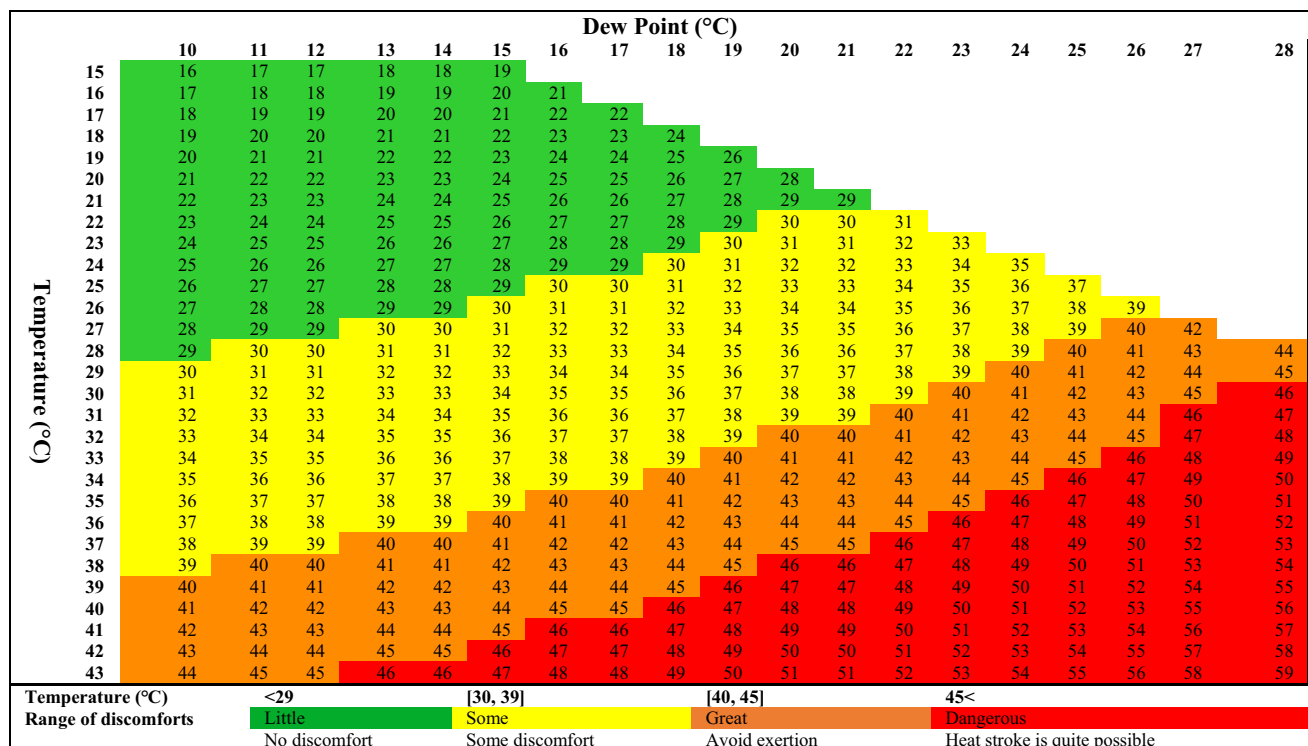


Fig. 4 Discomfort scale of Humidex

3.2.1 Anthropogenic climate change and heat-related deaths

A study conducted across 43 countries, including several European nations, has estimated that 37% of heat-related deaths can be attributed to anthropogenic climate change (Rocque 2021). The 2022 Lancet Countdown on Climate Change and Health Report indicates that heat-related mortality among individuals over 65 years of age has surged by nearly 70% over the past two decades in Europe (A. M. 2021). Advances in detection and attribution studies are enhancing our understanding and confidence in comprehending the health impacts of extreme weather events.

3.2.2 Cardiovascular (CV) health and rising temperatures

Addressing the critical intersection of global warming, heat waves, and cardiovascular health, a Portuguese Society of Cardiology position paper from 2023 aimed to address the impact of rising temperatures on cardiovascular diseases (CVDs) in Europe. It summarized data from key studies assessing the risks associated with temperature increases or heat waves in (CV) events. These events include CV mortality, myocardial infarction, heart failure, stroke, and CV hospitalizations (Bouchama and Knochel 2002).

This rise in heart rate and cardiac output increases myocardial demands, thereby increasing the risk of insufficient

coronary supply and hence myocardial infarction. These changes can also induce systemic inflammation and lead to a prothrombotic state, placing additional strain on the cardiovascular system, and predisposing vulnerable individuals to atherosclerotic plaque rupture which also increases the risk of myocardial infarction (Bouchama and Knochel 2002).

3.2.3 Temperature fluctuations and cardiovascular mortality

Studies across 27 countries, including many European nations, have explored the association between temperature fluctuations and CV mortality. Notably, both heat waves and cold spells have been linked to increased risks (Alahmad 2023). Therefore, the relationship between CV disease and temperature seems to be U-shaped.

3.2.4 Observational studies on heat-related mortality

Observational studies conducted across multiple European cities indicate that heat exposure significantly increases cardiovascular mortality and morbidity (Liu 2022). For instance, a review of ecological time series across 266 cases reveals that exposure to heat elevates cardiovascular mortality risks.

3.2.5 Epidemiological pathways linking heat exposure to CVD mortality

Epidemiological studies suggest several biological pathways linking heat exposure to CVD mortality (Alahmad 2023; Singh 2024). During extreme heat events, thermoregulatory mechanisms enhance vasodilation, increasing blood flow to the skin for heat dissipation (Desai et al. 2023). Furthermore, prolonged heat exposure can disrupt homeostasis, leading to dehydration, hemoconcentration, electrolyte imbalances, hypotension, inflammation, and excessive heart rate and cardiac output (Giorgini et al. 2017).

3.2.6 Real-world examples of heat-related mortality in Europe

One Portuguese study focused on the excess mortality and morbidity during the summer heat wave in Porto City (Ana Monteiro et al. 2006). The study aimed to investigate the impact of the July 2006 heat wave using the heat index. It focused on mortality (all causes) and morbidity (including respiratory and circulatory diseases) in the general population, as well as among individuals aged over 74 years and by gender, specifically in Porto (Ana Monteiro et al. 2006). The results found that a 1 °C increase in temperature raises the relative risk of overall CV mortality by 2.1%. Additionally, air pollution, especially common in urban areas, exacerbates global warming and amplifies the risk of CV events associated with temperature changes (Caldeira, et al. 2023).

3.2.7 Time-series analysis of thermal mortalities

Examining how extreme temperatures affect mortality rates in Scotland, a study using a 45-year dataset (1974–2018) and time-series regression analysis covered the four largest cities and three regions, identifying vulnerable groups such as the elderly and residents of deprived areas (Wan et al. 2022). The study underscores the heightened mortality risks linked to both severe cold and heat.

Research conducted across 800 locations in 50 countries utilized a two-stage time-series analysis to estimate location-age-specific temperature-mortality associations (Chen, et al. 1796). This analysis employed quasi-Poisson regression with distributed lag nonlinear models and multivariate random meta-regression, leveraging data from the Multi-Country Multi-City (MCC) Collaborative Research Network. By integrating these associations with bias-corrected future temperature series from 18 general circulation models (CMIP6) and future trends in age-specific baseline mortality, the study projected excess temperature mortality under three warming scenarios (1.5 °C, 2 °C, and 3 °C) and for the historical period (1995–2014). The findings highlight the significant role of population aging in influencing temperature-related

mortality, as evidenced by the differences in mortality fractions between climate-only and climate-population scenarios (Chen, et al. 1796). This underscores the necessity of considering demographic changes in future climate impact assessments.

3.2.8 Mortality and projection differences in the EU

Research that examined standardized mortality rates due to cold and heat across 1,368 European regions from 1991 to 2020 revealed considerable spatial differences in mortality rates. In this paper, the climate scenarios (+ 1.5°C, + 2°C, + 3°C, and + 4°C) have been adapted to the EU population projection trends by (2030, 2050, 2070, and 2100) (Projections n.d.; (ECOFIN) n.d.; Eurostat n.d.). This adoption makes it easy to understand the total (deaths/100k People) in different European Nations. Although cold spells have a larger impact than heat waves in Europe, increasing temperatures may have a dominant impact in some European countries.

Between 1991 and 2020, Europe saw an average of 407,538 temperature-related deaths annually, with 363,809 due to cold spells and 43,729 from heat waves, a median cold-to-heat mortality ratio of 8.3:1. Heat-related deaths had 20% greater variability than cold-related deaths, with both showing uneven impacts across regions. Regionally, northern Europe had low heat risk but moderate-to-high cold risk, southern Europe experienced high heat-related mortality and low cold-related mortality, and western Europe had relatively low risks for both. Eastern Europe, however, faced high risks for both heat- and cold-related deaths due to generally lower comfort levels. Mortality risks were also influenced by socioeconomic factors, with regional GDP per capita positively correlated with these risks.

Under a + 1.5°C warming scenario, Ireland is projected to have one of the highest cold-related mortality rates in Europe, with approximately 184 deaths per 100,000 people, while the Netherlands is among the lowest, with around 46 deaths per 100,000 people. For heat-related mortality, Malta is expected to experience one of the highest rates at about 52 deaths per 100,000 people, whereas Italy's rate is relatively low, at approximately 2 deaths per 100,000 people (100 k). These figures highlight significant regional disparities in climate-related mortality impacts, with Ireland and the Netherlands representing the most vulnerable and sustainable EU countries, respectively, under this scenario.

Under a + 2 °C warming scenario, cold-related mortality rates are highest in Ireland (176.5 deaths/100 k) and lowest in the Netherlands (42.5 deaths/100 k). Heat-related mortality rates show Malta as the most affected (72.2 deaths/100 k), while Ireland experiences the lowest rates (4.3 deaths/100 k). Malta and the Netherlands emerge as the most vulnerable

and sustainable countries, respectively, highlighting regional disparities in climate impacts (Winklmayr et al. 1992).

In a + 3 °C warming scenario, the ratio of heat to cold mortalities increases significantly. In Malta, heat-related deaths surpass cold-related deaths by 120.8 deaths/100 k, reflecting the growing burden of heat-related mortality in southern Europe as temperatures rise. Under the same scenario, Europe's cold-related mortality rates will stay mostly unchanged on average but will range between 29–225 deaths per 100,000 people, with decreases in eastern Europe and increases in Poland, Ireland, and Scandinavia. Heat-related mortality will rise significantly, from 2–117 deaths per 100,000, tripling the average rate to 30 deaths per 100,000, with the highest increases in southern Europe. Combined heat- and cold-related deaths will increase by 15% to 113.6 deaths per 100,000 people, adding approximately 54,974 deaths annually (Winklmayr et al. 1992).

By the end of the century, under a + 4 °C warming scenario, heat-related mortality rates exceed cold-related rates across the EU. Cold-related deaths range from 25 deaths/100 k in a Dutch region to 300 deaths/100 k in a Bulgarian region, with higher rates in eastern Europe. Heat-related deaths vary from 0.6 deaths/100 k in an Irish region to 47 deaths/100 k in a Croatian region, with southern Europe experiencing rates six times higher than northern regions. The cold-to-heat mortality ratio drops from 8.3:1 (1991–2020) to 1.4:1, driven by declining cold-related deaths and rising heat-related deaths, particularly affecting the elderly and lower-income population.

Aging populations are expected to have slightly reduced cold-related deaths in some regions (e.g., namely Bulgaria, and Baltic countries). Heat-related deaths will rise by 17.3 deaths per 100,000 on average, with larger impacts in southern Europe (3–4 times northern rates). Overall, combined changes will result in an additional 14.9 deaths per 100,000 annually, varying from –29 (Latvia) to +95 (Malta) (Winklmayr et al. 1992).

In brief, future areas of heightened risk for heat-related mortality are identified and located mainly in southern latitudes (Spain, Italy, Greece) and parts of France. Eastern regions will face intensified warming and reduced-intensity cold spells, but the total death risk will be mitigated by a decline in total mortality. Northern Europe will experience increased summer heat, but not enough to cause additional deaths, although the aging population will make the area more vulnerable to extreme heat episodes.

3.2.9 Vulnerability of the EU age groups

To understand the vulnerability of different age groups within the EU, this study categorizes age groups based on commonly accepted demographic divisions used in public

health and epidemiological research. The criteria for these age groupings are as follows:

- **Children (0–14 years):** This age group includes infants, children, and early adolescents. They are considered vulnerable due to their developing physiological systems and higher dependence on caregivers.
- **Adults (15–64 years):** This group encompasses working-age individuals. While generally more resilient, certain subgroups (e.g., pregnant women, and individuals with chronic illnesses) may be more susceptible to extreme temperatures.
- **Elderly (65 years and older):** Older adults are often the most vulnerable due to age-related physiological changes, pre-existing health conditions, and potentially social isolation.

The unadjusted excess death rates by age groups at the national level reveal distinct patterns (Masselot et al. 2023). The oldest age group experienced the highest impact from both cold and heat, with 36 (32 to 41) and 3 (3 to 4) excess deaths per 100,000 person-years, respectively. This accounted for approximately 44% of the total burden for cold and 38% for heat. Conversely, the youngest age group had about one death per 100,000 person-years due to cold, and less than one per 100,000 person-years due to heat.

The influence of cold is significant across all regions but tends to be lower in the western areas and higher in the northern and eastern areas, peaking at 174 (110 to 236) excess deaths per 100,000 person-years in Latvia. The effect of heat varies more widely, being minimal in the northern regions, except for Latvia and Lithuania, and significantly higher in the southern regions, with a peak of 27 (19 to 33) excess deaths per 100,000 person-years in Croatia (Masselot et al. 2023).

By specifying the criteria and basis for these age groupings, we can better understand the differential impacts of extreme temperatures on various segments of the population within the EU. This information is crucial for developing targeted interventions and public health strategies to protect the most vulnerable groups.

3.3 Climatic indexes and thermal stress

Health is influenced by more than just temperature alone. Interactions occur among temperature, relative humidity, wind, radiation, precipitation, and air pollution. These combined effects can be synergistic, exceeding the sum of individual impacts (Davis et al. 2016). While modeling such interactions can be complex, real-world scenarios emphasize their importance in studying temperature and heat effects on health (Singh 2024). For example, temperature alterations

impact human perception of humidity and can influence thermoregulation (Fang 2023).

Iran is an example of a medium-developed country, in which some areas have extreme temperatures, and facing health climate challenges. Assessing the heat stress-related mortality in Iranian Metropolitan areas utilized the Universal Thermal Climate Index (UTCI) as a measure to assess health risks associated with heat by analyzing climatic and health data, one study explored the correlation between high temperatures and increased mortality, demonstrating that heat stress can significantly affect public health (Faegheh Almasi and Rahimi 2023).

3.4 Urban energy climate mitigation planning strategies over literature

In terms of the urban cool surface materials, reflective pavements can decrease temperatures up to 10 °C while permeable pavements reduce temperatures by 5–10 °C. Both of the pavements reduce energy consumption by up to 15% (Vujovic et al. 2021). The findings highlight the significant impact of various building materials and low albedo strategies on mitigating the UHI effect while cool building envelope materials with high solar reflectivity can lower surface temperatures by 5–15 °C and reduce cooling energy demand by 20–30%. Reflective pavements and coatings can enhance surface reflectance by 30–50%, significantly reducing heat absorption. Green infrastructure, such as green roofs and vertical greenery systems, can lower ambient temperatures by 1–3 °C, contributing to urban resilience. Additionally, cool materials with high albedo values can maintain surface temperatures 10–15 °C lower than conventional materials. Also, the use of PVs causes slightly increasing UHI in the mesoscale while decreasing the UHI in micro-scale due to the shading process (Masson et al. 2014; Brito 2017). These findings underscore the effectiveness of these strategies in improving urban microclimates and reducing the adverse effects of UHI.

A detailed overview of recent research provided on medical strategies for UHI mitigation, focusing on cooling centers, heat health warning systems, and public health campaigns. The studies highlight the effectiveness of these strategies in reducing heat-related illnesses and mortality. For instance, cooling centers have been shown to reduce heat-related illnesses by 15–25% and improve access for vulnerable populations. US National strategies, such as the one outlined by the Biden-Harris Administration, emphasize the importance of integrating cooling centers, heat health warning systems, and public health campaigns to achieve a 30% reduction in heat-related mortality. Additionally, comprehensive heat-health action plans, as recommended by the WHO, can mitigate heat-related health impacts by 25%. These findings underscore the critical role of medical

strategies in enhancing community resilience to extreme heat.

A detailed overview of recent research on engineering strategies for UHI mitigation is provided focusing on advanced building technologies, climate-responsive architecture, and the integration of solar and wind energy (Ouria et al. 2024; Ouria 2019a). The studies highlight the effectiveness of these strategies in enhancing energy efficiency and reducing carbon emissions (Ouria and Almeida 2050). For instance, emerging technologies such as thermal energy storage and heat pumps can reduce building energy consumption by 20–30%. Climate-responsive buildings utilizing natural ventilation and mixed-mode systems can improve thermal comfort by up to 30% (Stechemesser et al. 2024). Case studies of energy-efficient building designs demonstrate energy savings of 15–25% across different climatic zones. Holistic design approaches in energy-efficient building design can reduce carbon emissions by 25–40%. Additionally, integrating renewable energy sources like solar and wind into building design can achieve net-zero energy targets, reducing energy costs by 30–50% (Stechemesser et al. 2024). These findings underscore the critical role of advanced building technologies and renewable energy integration in creating sustainable and climate-resilient urban environments (Ouria and Sevinc 2018; Ouria et al. 2023, 2016). Recently published case studies from Tabriz City fully support human thermal comfort with grid-independent solar systems following sustainable development criteria (Ouria et al. 2025).

In terms of technological and engineering strategies, building and transport electrification plays an important role. The transformation of the transportation market toward EVs shows 0.6 °C mitigation in UHIs but the use of solar PVs does have a complex impact on UHIs, due to the reduction of the local albedo. The PVs mitigate the UHIs by electricity decarbonization in general while the arrays increase the local point's temperature. The design of the solar PV installations should provide good natural ventilation of the panels to decrease local heating and improve the panels' efficiency.

4 Analysis methodology

The literature review highlighted the most promising strategies to be analyzed numerically. The reviewed data and statistics have been used in the quantitative study of strategies such as urban morphology (H/W, SVF, orientation), greenery infrastructure, NDVI, PCMs and low albedo materials, NDBI, emerging technologies, and emergency. The relative risk of heat-related mortalities has been calculated based on temperature variation due to each strategy and sensitivity coefficient of different human groups. It should be mentioned that these materials are estimated by focusing on the physical performance of strategies on UHI phenomena

in micro and mesoscale urban environments rather than the decarbonization process. Also, the reviewed successful policies have been categorized to highlight the importance of the decarbonization process in macro-scale and long-term UHI sector-by-sector.

The analysis of thermal risks and heat indicators involves a range of metrics, each offering unique insights into heat stress and its impacts. However, discrepancies may arise when different metrics yield varying risk calculations for the same environment. To address this, it is crucial to understand the specific contexts in which each metric is most reliable (Table 3).

By understanding the specific contexts and applications of each metric, researchers and policymakers can select the most appropriate and reliable indicators for their analyses. This approach ensures accurate and meaningful assessments of thermal risks and informs effective mitigation strategies.

4.1 Outdoor thermal comfort (OTC)

The OTC describes how comfortable people feel in outdoor environments, influenced by factors such as temperature, humidity, wind speed, and solar radiation, as well as personal aspects like clothing and activity. Ensuring OTC is essential for fostering well-being and promoting

outdoor activities in urban settings. Effective urban planning, including the addition of green spaces, shaded areas, water features, and the use of reflective materials, can significantly improve OTC by reducing heat stress. Prioritizing OTC contributes to better public health, lower energy consumption, and an enhanced quality of life for city residents. Several indexes described below are used to assess Outdoor Thermal Comfort.

4.1.1 Wind chill index (WCI)

The WCI reflects the perceived coldness experienced by humans outdoors (NWS 2024). It is calculated based on the heat loss rate from exposed skin due to wind and cold air. Higher wind speeds increase heat loss, lowering skin and internal body temperatures, thus making it feel colder (NWS 2024). For instance, at -30°C with a wind speed of 10 km/h, the wind chill temperature drops to -39°C , causing exposed skin to potentially freeze within 30 min while a more 5 km/h wind (15 km/hr.) makes a feel of (-41) only by exposure of 2 to 5 min (Table 4).

Table 5 lists the main findings of research papers investigating heat-related comfortless that used WCI as OTC as follows,

Table 3 Addressing Varied Metrics and Their Contextual Reliability

Metric	Context	Reliability
Wind Chill Index (WCI)	Cold climates and outdoor environments	Highly reliable for assessing perceived coldness, frostbite, and hypothermia risks
Wet Bulb Globe Temperature (WBGT)	Occupational health, sports, and military activities in hot climates	Comprehensive for measuring heat stress considering temperature, humidity, radiant heat, and air movement
Humidex	Public Weather Forecasting in Canada	Effective for indicating perceived temperature by combining air temperature and humidity
Heat Index (HI)	Public heat stress advisories in the United States	Reliable for reflecting how hot it feels to the human body by combining air temperature and relative humidity
Apparent Temperature (AT)/Human Perceived Temperature (HPT)	General human perception of weather conditions	Versatile for evaluating thermal comfort in various outdoor settings, combining effects of temperature, humidity, and wind speed
Standard Effective Temperature (SET)	Building design and HVAC system planning	Comprehensive for assessing indoor and outdoor thermal comfort, integrating multiple factors like temperature, humidity, air movement, and radiant temperature
Physiological Equivalent Temperature (PET)	Urban planning and climatology	Reliable for evaluating thermal comfort by considering the human body's heat balance in urban environments and outdoor spaces
Specific Meteorological Variables (SPMV)	Tailored to specific research needs in agriculture, climatology, and health	Adaptable for providing nuanced insights based on the study's requirements
Universal Thermal Climate Index (UTCI)	Global use in urban planning, public health, and climate impact studies	Comprehensive and versatile for assessing the outdoor thermal environment's effect on health and comfort across different climates and regions

Table 4 The Wind chill chart (°C), ranges and levels (EC [n.d.](#); Britannica [n.d.](#))

Wind Speed (km/h)	Air Temperature °C											
	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50
5	4	-2	-7	-13	-19	-24	-30	-36	-41	-47	-53	-58
10	3	-3	-9	-15	-21	-27	-33	-39	-45	-51	-57	-63
15	2	-4	-11	-17	-23	-29	-35	-41	-48	-54	-60	-66
20	1	-5	-12	-18	-24	-30	-37	-43	-49	-56	-62	-68
25	1	-6	-12	-19	-25	-32	-38	-44	-51	-57	-64	-70
30	0	-6	-13	-20	-26	-33	-39	-46	-52	-59	-65	-72
35	0	-7	-14	-20	-27	-33	-40	-47	-53	-60	-66	-73
40	-1	-7	-14	-21	-27	-34	-41	-48	-54	-61	-68	-74
45	-1	-8	-15	-21	-28	-35	-42	-48	-55	-62	-69	-75
50	-1	-8	-15	-22	-29	-35	-42	-49	-56	-63	-69	-76
55	-2	-8	-15	-22	-29	-36	-43	-50	-57	-63	-70	-77
60	-2	-16	-16	-23	-30	-36	-43	-50	-57	-64	-71	-78
65	-2	-16	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79
70	-2	-16	-16	-23	-30	-37	-44	-51	-58	-65	-72	-80
75	-3	-17	-17	-24	-31	-38	-45	-52	-59	-66	-73	-80
80	-3	-17	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81

Frostbite Guide						
Exposure Time (min)	30>		30-10		10-5	
Wind Chill (°C)	[0, -9]		[-10, -27]		[-48, -54]	
Exposure Risk	Low		Moderate		Severe	
Comfortless	Slightly		Discomfort		hypothermia	
Measurement	Stay dry, wear a warm dress		Wind-resistant layered dress, scarf, gloves, hat		Be careful, Cover all exposed skin with Wind wind-resistant layered dress, scarf, gloves, and hat.	

Table 5 Scientific findings regarding WCI and health

Short-Topic	Research Method	Index	Year of Study	Main Findings
Meaningful Wind Chill Indicators	Review, introducing new indicators	WCI	1995	Introduces new indicators like exposed skin temperature and maximum exposure time (Brauner and Shacham 1995)
Low Temperatures and Wind	ISO 11079, NORSOK S- 002 standards	WCI	2015	Reviews applicability in industrial settings and impact on worker safety (Wiggen et al. 2015)
Wind-Chill-Equivalent Temperatures	Mathematical and Simulation Studies	WCI	2006	Discusses development and updates, emphasizing heat loss expression in cold climates (Shitzer 2006)
The Wind-Chill Index	Historical overview	WCI	2021	Provides a historical overview and current applications, highlighting the significance of cold weather (Lankford and Fox 2021)
The lagged effect of cold temperature and WCI on mortality	Time-series analysis	WCI	2005	A delayed impact of cold temperatures and wind chill on cardiorespiratory mortality, meaning the effects are not immediate but occur several days after exposure (Carder 2005)

Table 6 The WBGT categories and US military guidelines

Heat Category	WBGT Range	Water Intake	Physical Activity	Flag Color
Low Risk	25.6-26.6°C	200-300 ml every 15 minutes	Continuous work	White
Moderate Risk	26.7-29.4°C	200-300 ml every 15 minutes	50 minutes work / 10 minutes rest	Green
High Risk	29.5-31.1°C	300-500 ml per hour	40 minutes work / 20 minutes rest	Yellow
Very High Risk	31.2-32.1°C	300-500 ml per hour	30 minutes work / 30 minutes rest	Red
Extreme Risk	>32.2°C	300-500 ml per hour	20 minutes work / 40 minutes rest	Black

4.1.2 Wet bulb globe temperature (WBGT)

The WBGT is a comprehensive measure that includes air temperature, humidity, radiant heat, and air movement to

assess heat stress (Lemke and Kjellstrom [2012](#)). In hot climates, some US military bases use a flag system to indicate heat categories based on WBGT readings (Moran et al. [1998](#)). The military also provides guidelines for water intake

Table 7 Findings regarding the WBGT index

Short Topic	Main Aim	Main Findings	Methodology	Year
Comparison of heat-related mortality in urban and rural areas	To compare heat-related mortality rates between urban and rural areas using WBGT	The study found differences in heat-related mortality rates, with WBGT effectively measuring heat stress impacts (Odame et al. 1597)	Comparative study	2021
Heat stress in agricultural workers	To study the impact of heat stress on mortality rates among agricultural workers using WBGT	WBGT was used to measure heat exposure, revealing a strong correlation between heat stress and mortality rates in agricultural workers (Odame 2019)	Observational study	2019
Vulnerability of elderly populations to heat stress	To examine the risk of heat-related mortality in elderly populations using WBGT	The study found that elderly populations are particularly vulnerable to heat stress, with WBGT effectively assessing the risk (Ueno et al. 2021)	Cross-sectional study	2020
Impact of urban heat islands on mortality	To explore the effect of urban heat islands on heat-related mortality using WBGT	The study found that urban heat islands significantly increase heat-related mortality, with WBGT as a useful measurement tool (Hsu et al. 2721)	Case study analysis	2021
Heat stress in outdoor workers	To investigate the impact of heat stress on mortality rates among outdoor workers using WBGT	WBGT was used to assess heat exposure, showing a strong correlation between heat stress and mortality rates in outdoor workers (Habibi et al. 1711)	Systematic literature review	2024
OTC & UHI management	To understand the role of WBGT in HW-UHI synergies and their impact on thermal comfort	Diurnal UHI consistently amplified during WBGT-HWs, especially between 11:00–17:00 LST. (He et al. 2020)	Analytical Comparative study	2020

and physical activity for both acclimated and unacclimated individuals, tailored to different uniforms and heat categories that are presented in Table 6. (Sawka et al. 2011).

Table 7 lists the literature review of studies that focused on heat-related health issues using WBGT as the measure index.

4.1.3 Humidex

The Humidex index focuses on the feel of hot weather under humidity (Wellenius 2017). For instance, when the Humidex reads 32 °C, it means that the combined sensation of heat and humidity feels like 32 °C to a person, regardless of the actual air temperature (Fig. 4). Elevated Humidex values signify increased discomfort and potential health hazards, particularly for at-risk groups (Li, et al. 2024).

There are relevant investigations that focused on heat-related mortality in different cities highlighting the role of humidity using the Humidex index (Table 8).

4.1.4 Heat index (HI)

According to the US National Weather Service, the phrase “It’s not the heat, it’s the humidity” is partly true, but both factors play a role in how hot it feels (NWS 2024b). The HI or apparent temperature, combines air temperature and relative humidity to reflect how hot it feels to the human body. This is crucial for understanding human comfort. When the body overheats, it sweats to cool down. If sweat cannot evaporate due to high humidity, the body struggles to regulate its temperature. Evaporation cools the body, so when humidity is high, evaporation slows, making the body feel warmer (NWS 2024b). Conversely, in dry conditions, sweat

evaporates quickly, making the body feel cooler. The Heat Index increases with higher air temperature and humidity. For example, at 38 °C with 55% humidity, the Heat Index is 51 °C. Conversely, at 38 °C with 65% humidity, it feels like 58 °C. In regions with low humidity, dangerous Heat Index values (39 °C or higher) are less common (Table 9). Heat Index values are typically calculated for shaded areas. Direct sunlight can increase these values by up to 8 °C. Heat indices of 39 °C or higher can lead to dangerous heat-related health issues with prolonged exposure or physical activity.

The peer-reviewed papers that assessed the heat impacts on human health using the HI are listed in Table 10 as follows.

4.1.5 Apparent temperature (AT) or human-perceived temperature (HPT)

The AT, often referred to as the “feels like” temperature, is a measure that combines air temperature, relative humidity, and wind speed to reflect how hot or cold it feels to humans (Fig. 5). It also is known as Human-Perceived Temperature (HPT) (Steadman 1979a; Lee et al. 2021). The AT can be seen as a combination of the (HI) and (WCI), depending on whether the conditions are hot or cold. It reflects how the human body perceives temperature by considering these factors (Steadman 1984).

The temperature category and their impacts on the human body are the same as mentioned for HI. The AT has been used to evaluate human comfort zones in urban spaces across the world. The findings show a significant impact of environmental factors on human health in China (Table 12). Assessing the link between AT and non-accidental deaths in Asia shows regional differences in mortality

Table 8 The importance of Humidex in scientific findings

Short-Topic	OTC Index	Number of Cases	Place	Main Finding	Year
Humidity on City-Level Mortality	Humidex	739 cities	Global	Humidex works better where the temperature and humidity correlation are close to 0 (Guo, et al. 2024)	2024
Forecasting Mortality Under Climate Change	Humidex	Various studies	Various locations	A combination of temperature with humidity is required for mortality prediction where UHI is noticeable (Paravantis 2022)	2023
Humidex on Cardiovascular Mortality	Humidex	Multiple cities	Various locations	A higher Humidex value increases CVD mortalities. The humidity should be regarded in predictions (Li, et al. 1916)	2023
Measuring Meteorological Mortality	Humidex	Beijing	Beijing	The Humidex index was a better predictor of heat-related mortality compared to temperature alone (Yin and Wang 2018)	2018
Heat-Related Mortality in Washington	Humidex	Various locations	Washington State	The mortality increased by 8% when the Humidex was in the top 1% of recorded values (Hannah Hickey and Scheuerell n.d.)	2022

Table 9 The (HI)scale, classification, and effects on the human body (NWS 2024b; Steadman 1979a, 1979b)

RH%	Temperature (°C)												
	27	28	29	30	31	32	33	34	36	37	38	39	40
40%	27	27	28	29	31	33	34	36	38	41	43	46	48
45%	27	28	29	31	32	34	36	38	40	43	46	48	51
50%	27	28	29	31	33	35	37	39	42	45	48	51	55
55%	27	29	30	32	34	36	38	41	44	47	51	54	58
60%	28	29	31	33	35	38	41	43	47	51	54	58	
65%	28	29	32	34	37	39	42	46	49	53	58		
70%	28	30	32	35	38	41	44	48	52	57			
75%	29	31	32	36	39	43	47	51	56				
80%	29	32	34	38	41	45	49	54					
85%	29	32	36	39	43	47	52	57					
90%	30	33	37	41	45	50	55						
95%	30	34	38	42	47	53							
100%	31	35	39	44	49	56							
Classification	Heat Index						Effect on the body						
Caution	27°C – 32°C						Fatigue is possible with prolonged exposure and/or physical activity						
Extreme Caution	32°C – 39°C						Heat stroke, heat cramps, or heat exhaustion are possible with prolonged exposure and/or physical activity.						
Danger	40°C – 51°C						Heat cramps or heat exhaustion is likely, and heat stroke is possible with prolonged exposure and/or physical activity.						
Extreme Danger	51°C<						Heat stroke is highly likely						

Table 10 HI in scientific findings

Short Title	Main aim	Research Method	Key Findings	Year
Heat Index and Mortality in the US	To explore the relationship between the Heat Index and heat-related deaths in the US	Analysis of regional mortality data	Significant impact of extreme heat on various demographics (Sheridan et al. 2018)	2021
Heat Index in Urban Areas	To assess heat-related mortality risk using the Heat Index in urban areas	Urban mortality data analysis	High incidence of heat-related deaths in urban heat islands (Niu, et al. 2021)	2022
Heat Index as Predictor in EU	To evaluate the Heat Index as a predictor of heat-related mortality in Europe	Comparative analysis of European data	Effective predictor compared to other heat metrics (Lüthi, et al. 2023)	2023
Heat Index and Mortality Trends	To understand trends in heat-related mortality using the Heat Index	Analysis of historical and projected data	Historical and future trends in heat-related deaths (Hajat and Kosatky 2010)	2010
Heat Index and Vulnerability	To examine the relationship between the Heat Index and vulnerability to heat-related mortality	Vulnerability assessment using mortality data	Identification of key risk factors in different populations (Davis 2021)	2021

risk. Regional climate modeling by the AT in Africa monitored an increased frequency of extreme AT days and their health impacts. UHI significantly affects outdoor comfort by increasing AT (Table 11).

4.1.6 Standard effective temperature (SET)

The SET is a comprehensive thermal comfort index that was accepted by ASHRAE in 1986, and integrates air temperature, mean radiant temperature, humidity, and airspeed to estimate the perceived temperature by the human body (Ji, et al. 2022). It is utilized to assess thermal comfort in both indoor and outdoor settings, considering various factors that influence heat exchange between the human body and its environment. Evaluating thermal comfort in urban parks using SET discloses that vegetation and water bodies significantly enhance comfort levels (Liu et al. 2023a), (Table 13).

Also, urban geometry impacts the human outdoors (Ouria and Sevinc 2018; Ouria 2019b), (Table 12).

4.1.7 Physiological equivalent temperature (PET)

The PET index is designed to evaluate thermal comfort by considering the human body's heat balance Walther (2018). It is derived from the Munich Energy-balance Model for Individuals (MEMI), which accurately simulates the thermal conditions experienced by the human body (Höppe 1999). PET integrates weather data and physiological parameters, including clothing and human activities, to measure thermal comfort in urban planning and building design (Höppe 1999), (Fig. 6).

According to the literature review listed in Table 13, PET values are essential for determining thermal comfort, showing that thermal comfort can differ by up to 5 °C depending

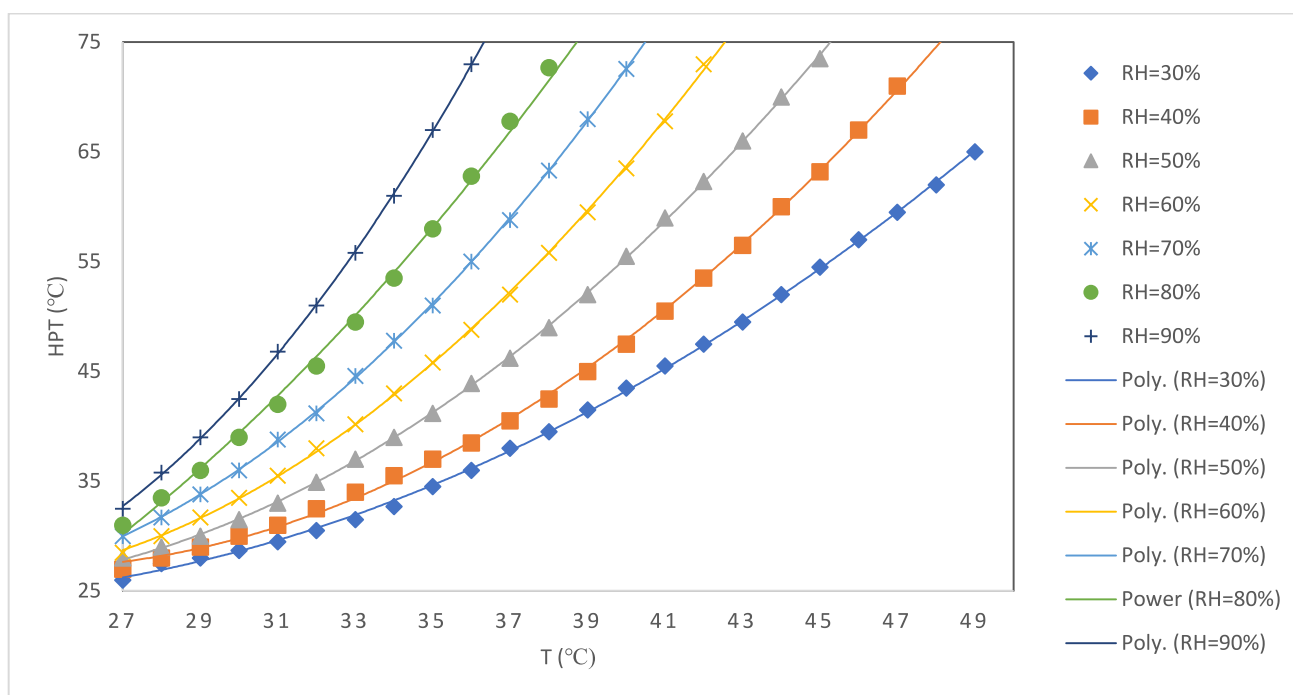


Fig. 5 Relationship between RH (%) and temperature (°C) for HPT (°C), (Lee et al. 2021)

Table 11 AT in scientific findings

Short Title	Research Method	Main Objective	Key Findings	Year
AT Comfort Zone in China	Analysis of HI data from meteorological stations	To evaluate human comfort using Apparent Temperature in China	Significant impact of environmental factors on health (Wang et al. 2022)	2022
AT and Mortality in Asia	Time-series regression with DLNM	Assessing the link between AT and non-accidental deaths in Asia	Regional differences in mortality risk (Cao, et al. 2021)	2021
Extreme AT Days in Africa	Regional climate modeling	To project extreme AT days and their health impacts in Africa	Increased frequency of extreme AT days (Garland, et al. 2015)	2015
UHI Impact on Outdoor Comfort	Review of OTC evaluation indexes	To review the impact of Urban Heat Islands on outdoor thermal comfort	UHI significantly affects outdoor comfort by increasing AT (Ren et al. 1368)	2023
Thermal Comfort in Urban Spaces	Review of OTC evaluation methods	To review factors affecting OTC and improvement strategies	Various factors influence outdoor comfort (Liu et al. 2023a)	2023

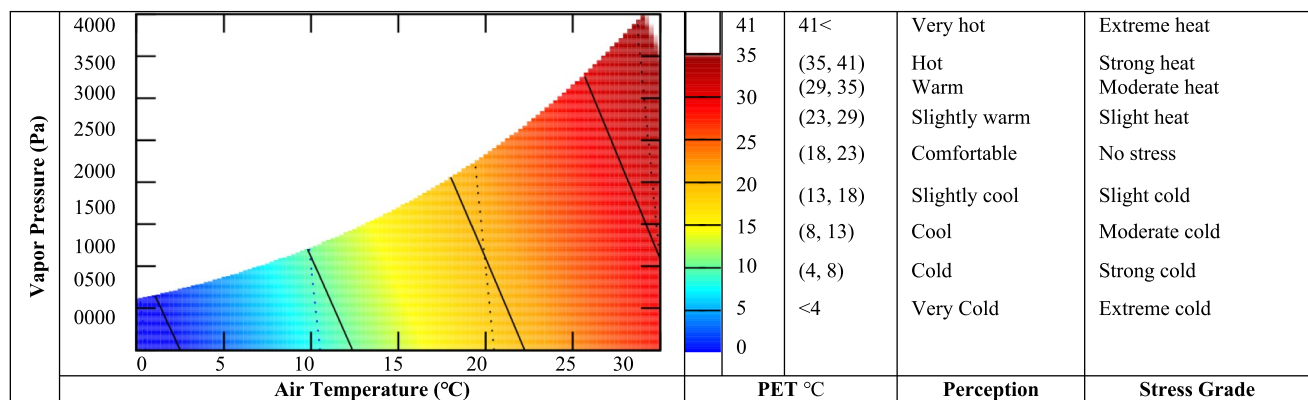
on microclimatic conditions (Elnabawi and Hamza 2020; Nikolopoulou et al. 2021). Empirical Studies show the PET benchmarks indicated a reduction of up to 10 °C in areas with climate-responsive designs (Yuan et al. 2023). Also, PET values were used to model thermal comfort, showing a 15% increase in comfort levels with proper shading and ventilation (Deng et al. 1357). A comparative study of urban outdoor thermal environments during heatwaves by PET showed differences of up to 8 °C, emphasizing the importance of local climate adaptation (Walther 2018; Zhen et al. 2022).

4.1.8 Specific meteorological variables (SPMV)

The SPMV index is designed to evaluate OTC settings. It is derived from the Predicted Mean Vote (PMV) model, which predicts the average thermal sensation of a group of people on a scale from cold (− 3) to hot (+ 3) (Cakó, et al. 2021), (Fig. 7). The SPMV adapts this model for outdoor environments by considering factors such as air temperature, humidity, wind speed, and radiant temperature (Aghamolaei et al. 2023). This index provides a nuanced understanding of thermal comfort in various climates and cultural contexts,

Table 12 SET in scientific research

Short Title	Research Method	Main Objective	Key Findings	Year
SET in Urban Parks	Field measurements and SET calculations	To assess thermal comfort in urban parks using SET	Vegetation and water bodies significantly enhance comfort levels (Liu et al. 2023a)	2022
Urban Geometry and SET	Computational fluid dynamics and SET analysis	To investigate the impact of urban geometry on OTC using SET	Different urban geometries have varying effects on comfort (Wai et al. 2024; Visvanathan et al. 2024)	2021
SET in Public Spaces	Field surveys and SET assessments	To evaluate thermal comfort in public spaces using SET	Shading and ventilation play crucial roles in enhancing comfort (Khan et al. 2021)	2023
Climate Change and SET	Climate modeling and SET projections	To examine the impact of climate change on OTC using SET	Future climate scenarios indicate reduced comfort levels	2022
UHI and SET	Analysis of UHI effects using SET	To explore the relationship between UHI and thermal comfort using SET	UHI significantly increases perceived discomfort (Kalogeropoulou et al. 2023)	2023

**Fig. 6** PET index for thermal comfort (Prata-Shimomura et al. 2010; Walther 2018)

making it a valuable tool for urban planners and designers to enhance outdoor thermal environments (Fabbri 2024).

Based on OTC investigations, the SPMV provides a more detailed understanding of thermal comfort in climatic and cultural aims (Stack n.d.). It assumes elevated solar exposure and humidity ranges and provides a reliable approach to OTC (Mitra et al. 2018). Field surveys and measurements, including the SPMV index in thermal conditions in urban parks, highlight design recommendations for enhancing park comfort (Thorsson et al. 2004). Another research highlights that the integration of SPMV and CFD modeling provides a comprehensive approach to improving thermal comfort (Jin and Yoon 2023). The role of urban design and surface materials has been significantly noticed regarding OTC in Urban Areas (Lin et al. 2024) as listed in Table 14.

4.1.9 Universal thermal climate index (UTCI)

The UTCI as a bioclimatic index of OTC considers radiation, wind speed, humidity, and air temperature to evaluate AT that the human feels under specific conditions (Bröde, et al. 2012), (Fig. 8). It is important due to its effective variables (Krüger and Krüger 2021). The UTCI classifies thermal stress into ten distinct levels from severe cold stress (below -40°C) to severe heat stress (above $+46^{\circ}\text{C}$). For instance, a UTCI value between 9°C and 26°C signifies an absence of thermal stress, making it ideal for outdoor activities (Climate Adapt 2024; Failed 2024b).

The research focused on enhancing OTC in arid and hot climates through optimized urban design by utilizing the UTCI to gauge comfort levels (Table 15). The study employs a genetic algorithm to refine urban block layouts in Kashgar

Table 13 PET in scientific research

Short Title	Methodology	Main Aim	Main Result/Findings	Year
Behavioral Perspectives of Outdoor Thermal Comfort	Literature Review	To analyze studies on outdoor thermal comfort with a focus on behavioral aspects	PET values are essential for determining thermal comfort, showing significant variations based on behavioral adaptations (Elnabawi and Hamza 2020)	2020
Thermal Comfort in Urban Spaces	Literature Review	To explore the impact of microclimatic and thermal comfort conditions on urban space usage	PET values revealed that thermal comfort can differ by up to 5 °C depending on microclimatic conditions (Nikolopoulou et al. 2021)	2021
Climate-Responsive Designs to Enhance Outdoor Thermal Comfort	Empirical Study	To establish outdoor thermal benchmarks and suggest climate-responsive strategies	PET benchmarks indicated a reduction of up to 10 °C in areas with climate-responsive designs (Yuan et al. 2023)	2023
Outdoor Thermal Comfort and Activities in Subtropical China	Empirical Study	To investigate outdoor thermal comfort and activities of residents	PET values were used to model thermal comfort, showing a 15% increase in comfort levels with proper shading and ventilation (Deng, et al. 1357)	2022
Urban Outdoor Thermal Environment During Heatwaves	Comparative Study	To examine thermal conditions in outdoor spaces during heatwaves	PET values in Singapore and Changsha showed differences of up to 8 °C, emphasizing the importance of local climate adaptation (Zhen et al. 2022)	2022

(Xu et al. 2019). The findings indicate a notable reduction in both UTCI and mean radiant temperature (MRT) during summer, underscoring the role of urban morphology in reducing heat stress and enhancing outdoor comfort. The UTCI and health outcomes in Bavaria a 5% increase in mortality and a 7% increase in hospital admissions during summer (Ghada et al. 2021) while a comparison of UTCI with other thermal indices shows a 10% increase in cardiovascular mortality during extreme heat in the Czech Republic (Urban and Kyselý 2014). A long-term analysis of UTCI and mortality in Poland shows a 15% increase in mortality during heat waves (Kuchcik 2021).

A global monthly UTCI dataset has been analyzed using advanced machine learning models from 2000 to 2022 with surprising results (Yang et al. 2024). The average yearly global UTCI was 17.24 °C, showing a clear upward trend throughout the study period. Russia and Brazil were major contributors to this rise, whereas China and India had a more restraining effect (Fig. 9).

The study identified CatBoost (Xu et al. 2019) as the optimal model for estimating global monthly UTCI, enabling the creation of the GloUTCI-M dataset (1 km resolution) from 2000 to 2022. An analysis of 2021 data revealed key spatial and seasonal patterns. In the Northern Hemisphere, UTCI values declined with latitude, especially during winter, while the Southern Hemisphere showed less variation. Summer months featured high UTCI values (> 40 °C), while winter months in the Northern Hemisphere had abundant low UTCI pixels. A line plot of annual UTCI data (Fig. 9 m) highlighted regions with relatively high UTCI, including northern South America, northern Africa, southern Asia, and Australia. Table 20 summarizes the key aspects of each index, its purposes, components, and applications.

4.2 UHI mitigation strategies

The urban land use and land cover cause varying land surface temperatures and generate UHIs due to the different shapes, materials, densities, and compactness of the different blocks (Ouria 2019b). The UHIs not only require overloaded energy to balance the temperature but also impact OTC quality negatively (Ouria and Sevinc 2018). Examining various strategies to mitigate the UHI effect underscores three critical parts including: A) Urban morphology, form, and geometry, B) Green envelopes including green roofs, vertical greenery systems, and pedestrian pavements, and C) Building materials and low albedo. The need for incorporating these green infrastructures into urban planning to decrease ambient temperatures and enhance urban living environments is vital (Aflaki, et al. 2017).

As awareness of the detrimental effects of the UHI phenomenon grows, mitigating this issue has become a prominent social concern (Ouria 2019a; Han et al. 2023). Several

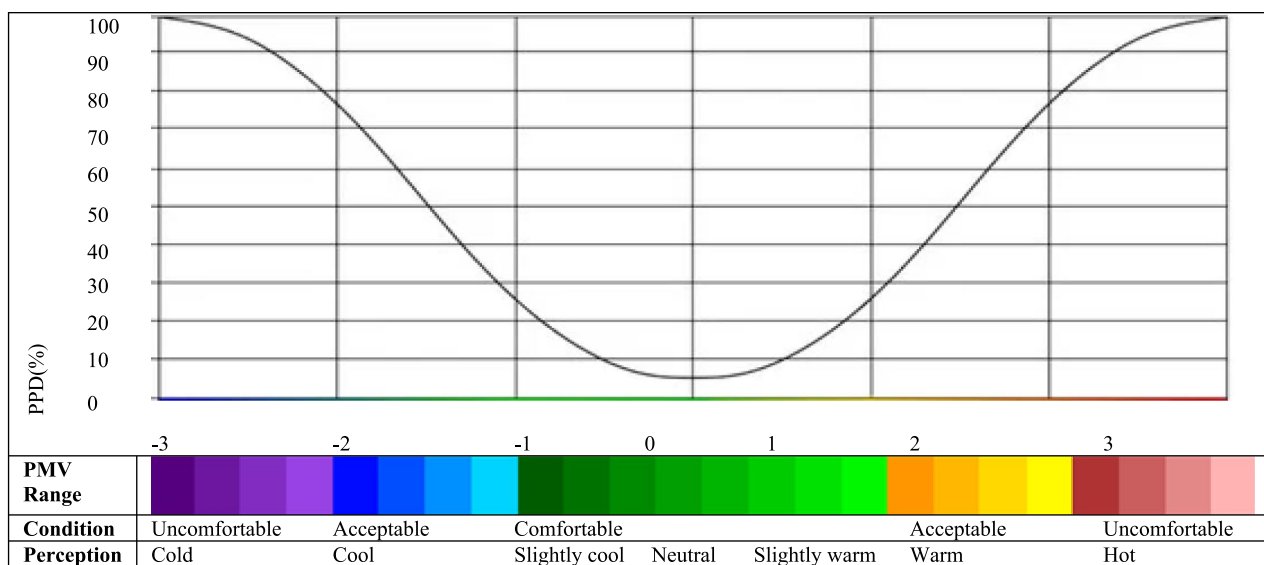


Fig. 7 Predicted Mean Vote (PMV) Curve (Cakó, et al. 2021; A. AC08024865 2005)

strategies can be employed to address these impacts, based on the understanding of UHI formation. These strategies include utilizing highly reflective materials (Han et al. 2023; Santamouris 2013; Akbari and Matthews 2012), improving green infrastructure (Ouria and Almeida 2050; Matthews et al. 2015), enhancing urban design and structure (Ouria 2019b; Tan et al. 2016), increasing the presence of urban wetlands and water bodies (Han et al. 2023; Abahri et al. 2011), and medical emergency strategies. Implementing these measures addresses the interconnected concerns of energy, the environment, and human activities following sustainable development dimensions.

4.2.1 Urban morphology

Urban morphology encompasses the physical structure, layout, and design of a city. It significantly impacts the intensity of the UHI effect (Ouria and Sevinc 2018; Benaomar and Outzourhit 2024; Zhou et al. 2017). Key components of urban morphology that influence UHIs include surface roughness, building shapes and densities, and the configuration and orientation of streets (Li et al. 2020; Hou et al. 2023; Ayten Ozsavas et al. 2014). The vertical and spatial concentration of buildings can significantly disrupt the urban energy balance by intensifying solar radiation absorption, casting extensive shadows, and impeding airflow (Ouria et al. 2024; Coutts et al. 2007). Empirical studies indicate that such disruptions to the energy balance can cause elevated ambient temperatures and reduced thermal comfort within urban canyons (Benaomar and Outzourhit 2024; Oswald et al. 2019). The design and positioning of streets in urban areas (Fig. 10) determine their exposure to solar

radiation and airflow, impacting their ability to retain heat. This affects the intensity and spatial variation of the Urban Heat Island (UHI) effect (Takebayashi and Moriyama 2012). The aspect ratio of street canyons is defined as the height of buildings divided by the street. The AR is negatively correlated with the sky view factor (SVF) and significantly influences UHI dynamics, depending on the regional climate.

The SVF serves as a metric to evaluate the building arrangement and density in urban areas (Fig. 10). SVF represents the proportion of the sky hemisphere visible from a specific ground point, unobstructed by urban elements such as buildings, terrain, or trees (Han et al. 2023; Oke 1988). A smaller SVF indicates denser building distribution and reduced ground-level solar radiation. Numerous studies have explored the impact of SVF on urban microclimate (Correa et al. 2012). Lower SVF leads to lower daytime temperatures and higher nighttime temperatures in urban canyon regions (Svensson 2004). This is because canyons with low SVF obstruct solar radiation, reducing net solar gain during the day, and thereby lowering air temperatures. Conversely, at night, low SVF impedes long-wave radiation from escaping the ground surface, slowing the cooling process of urban canyons and resulting in higher nighttime air temperatures (De and Mukherjee 2018).

Indicators such as the normalized difference vegetation index (NDVI), normalized difference built-up index (NDBI), and modified normalized difference water index (MNDWI) are essential regarding urban morphology and greenery spaces (Keerthi Naidu and Chundeli 2023; Chaudhary et al. 2022; Alademomi, et al. 2022, 1661; Ullah et al. 2024; Khan et al. 1018; Javaid, et al. 2023). They are available in Landsat satellite imagery services. The population density

Table 14 SPMV in scientific research

Short Title	Research Methodology	Main Aim	Main Result/Highlighted Findings	Year
Outdoor Thermal Comfort Indexes: UTCI vs SPMV	Comparison of UTCI and SPMV indices	To compare the effectiveness of UTCI and SPMV in assessing outdoor thermal comfort	SPMV provides a more detailed understanding of thermal comfort in specific climates and cultural contexts (Stack n.d.)	2023
SPMV Thermal Comfort Criteria Explained	Literature Review	To explain the SPMV metric and its application in outdoor environments	SPMV effectively accounts for elevated solar exposure and humidity ranges, providing a comprehensive approach to outdoor thermal comfort (Mitra et al. 2018)	2023
Thermal Conditions in Urban Park	Field survey and measurements, including SPMV index	To explore the link between the thermal environment and park usage	Thermal comfort changes with weather and seasons; visitor behavior is influenced by thermal conditions; design recommendations for enhancing park comfort (Thorsen et al. 2004)	2003
Evaluating Thermal Comfort in Outdoor Spaces	Combination of SPMV and (CFD) modeling	To assess the thermal comfort of outdoor spaces and propose design improvements	Integration of SPMV and CFD modeling provides a comprehensive approach to improving thermal comfort (Jin and Yoon 2023)	2023
OTC in Urban Areas	Empirical Study	To assess thermal comfort in urban areas	SPMV results indicated significant variations in thermal comfort based on urban design and materials (Lin et al. 2024)	2022

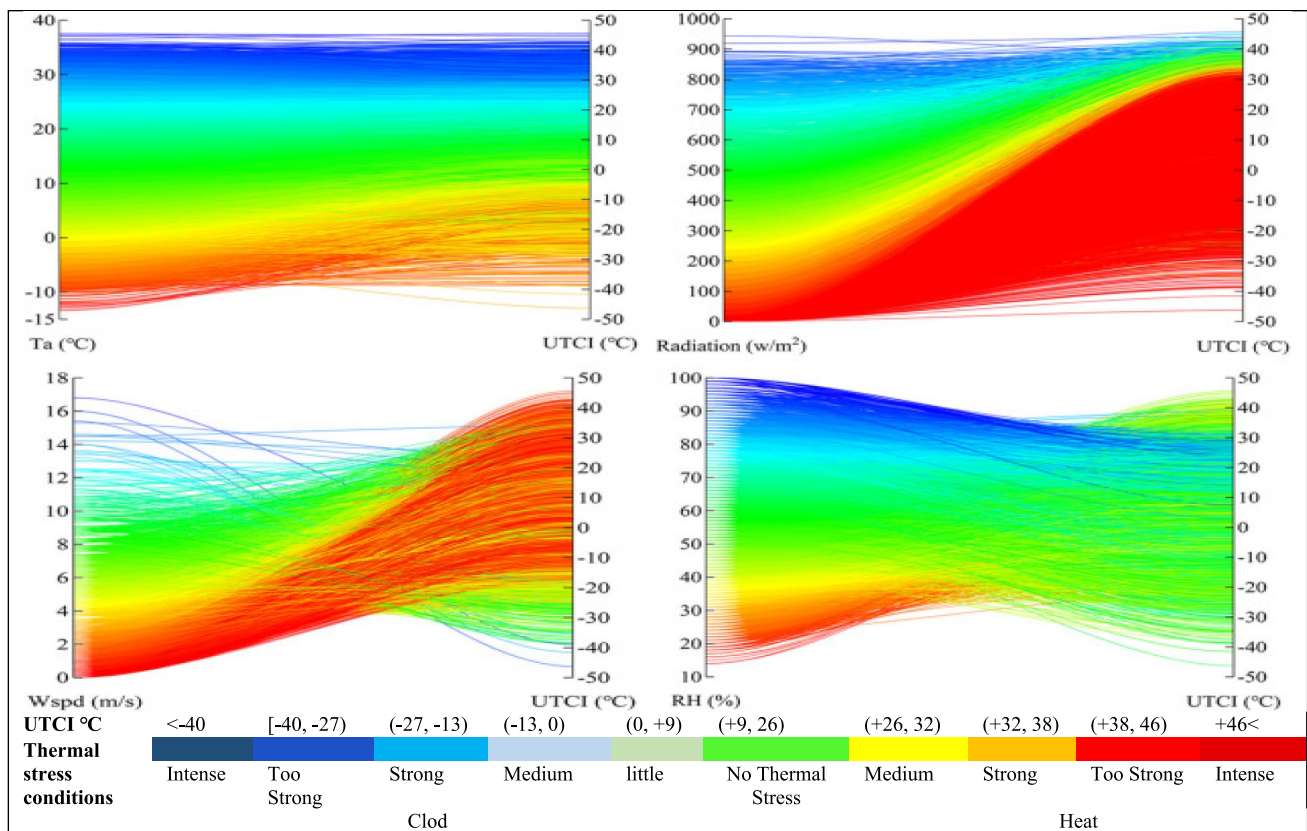


Fig. 8 Thermal classification of UTCI index based on climatic and physiological criteria (Faegeh Almasi and Rahimi 2023; Blazejczyk et al. 2012; Nie et al. 2022)

(PD) metric is also obtainable from population raster data. Together, these indicators represent diverse facets of building structures, ecological infrastructure, and human activities (Liu et al. 2023b).

Urban land use and land cover cause varying UHIs due to the different shapes, materials, densities, and compactness of the different blocks. They mostly used GIS data for UHIs measuring while the Ladybug & Honeybee plug-in Rhino simulator was used for micro-scale thermal behaviors (Ouria et al. 2016; Wai et al. 2024; Xu et al. 2019). The list of software that is used to analyze urban morphology and UHIs is presented in Fig. 11.

Figure 11, represents the diversity index, N denotes the total number of individuals, and n signifies the number of individuals (Liu et al. 2023b). R is the volume ratio, Q indicates the total area of the space unit building, and S refers to the plot area. $n = 360$, and γ_i is the observer's line of sight direction. L represents the number of stories, and H denotes the height of each story. NIR indicates the reflectance in the near-infrared band, Red corresponds to the reflectance in the red band of the visible spectrum, Green refers to the

visible green band, and SWIR indicates the reflectance in the shortwave infrared band.

4.2.2 Humidity & heat-related mortalities analysis

Analyzing the impact of relative humidity (RH) on heat-related mortalities is crucial for developing effective mitigation strategies across different regions, including Asian (Chinese), European (EU), and American cities (Guo, et al. 2024; Armstrong et al. 2019; Barreca 2012). By incorporating RH levels into heat-health alert systems and predictive models, cities can better anticipate periods of elevated risk and implement targeted interventions (Fang 2023; Bu, et al. 2024). For example, in Chinese cities like Beijing and Chengdu, high RH significantly contributes to increased mortality rates during extreme temperatures. Similarly, EU cities such as Milan and Mediterranean cities experience substantial mortality increases during heat waves due to high RH. In American cities like Atlanta and Phoenix, RH amplifies the adverse effects of heat, leading to higher mortality rates. Crafting region-specific measures, such as establishing

Table 15 UTCI in scientific research

Short Title	Research Methodology	Main Aim	Main Result/Highlighted Findings	Year
Urban Morphology & OTC by GA	Field survey, optimization	Enhancing OTC in arid and hot climates	A notable reduction in UTCI is 3.74 °C during summer, highlighting the role of urban morphology in reducing heat stress and enhancing OTC (Xu et al. 2019)	2019
UTCI and Health Outcomes in Bavaria	Observational Study	To examine the relationship between UTCI and health outcomes	Higher UTCI values are linked to a 5% increase in mortality and a 7% increase in hospital admissions during summer (Ghada et al. 2021)	2023
Review of UTCI Applications	Literature Review	To compile studies on UTCI applications	Highlights the broad applicability of UTCI in assessing human health impacts and outdoor thermal comfort (Krüger and Krüger 2021)	2022
Comparison of UTCI with Other Thermal Indices	Comparative Study	To compare UTCI with other indices in analyzing heat- and cold-related effects on cardiovascular mortality	UTCI is a reliable indicator for assessing thermal stress-related health risks, showing a 10% increase in cardiovascular mortality during extreme heat (Urban and Kysely 2014)	2021
Long-term Analysis of UTCI and Mortality in Poland	Long-term Observational Study	To examine changes in extreme OTC measured by UTCI effects on mortality	Extreme thermal conditions significantly impact mortality rates, with a 15% increase in mortality during heatwaves (Kuchcik 2021)	2021

cooling centers, conducting public education campaigns, and enhancing emergency response plans, can help minimize the adverse health effects of extreme weather. Additionally, targeting vulnerable populations ensures that support reaches those most at risk during high humidity and heat events.

4.3 Microclimate indices & thermal comfort conversions

The geometric and morphologic features impact microclimate and thermal comfort indices. Alongside air temperature (AT), surface temperature (ST), relative humidity (RH), and wind speed (WS), the influence of SVF on thermal comfort is assessed through Mean Radiant Temperature (MRT) and Predicted Mean Vote (PMV). MRT (in Kelvin) indicates the overall radiation absorbed by the human body and is significantly impacted by urban design and the materials used in surfaces (Höppe 1999; Qaid et al. 2016; Lyu et al. 2019). MRT can be defined as,

$$MRT = \left[\frac{1}{\sigma_B} \left(E_t(z) + \frac{a_k}{\epsilon_p} (D_t(z) + I_t(z)) \right) \right]^{0.25}$$

where $E_t(z)$, $D_t(z)$, and $I_t(z)$ Represent long-wave radiation, direct short-wave radiation, and diffuse short-wave radiation, respectively, measured in watts per square meter (W/m^2). The Stefan-Boltzmann constant, σ_B , is $5.67 \times 10^{-8} (W/m^2 \cdot K^4)$. The human body has an absorption coefficient, α_k , of 0.7 for short-wave radiation, and an emission coefficient, ϵ_p , of 0.97 (Rui et al. 2019). Also, there are several methods and tools to measure MRT such as black globe thermometers (BGT), acrylic globe thermometers (AGT), cylindrical radiation thermometers (CRT), radiometers, six-directional method, and infrared thermography. Calculating LST from Landsat 9 data consists of three stages. First, digital numbers (DN) should be converted to radiance as follows,

$$L_\lambda = ML \cdot Q_{cal} + AL$$

where, L_λ is spectral radiance [$W/(m^2 \cdot sr \cdot \mu m)$]. ML is a radiance multiplicative scaling factor (from metadata). Q_{cal} Is quantized and calibrated standard product pixel values (DN). AL imposes a radiance additive scaling factor (from metadata). Second, the radiance should be converted to brightness temperature as follows,

$$T_{BT} = \frac{K2}{\ln\left(\frac{K1}{L_\lambda}\right)}$$

where, T_{BT} Is brightness temperature (Kelvin). $K1$ and $K2$ represent calibration constant (from metadata). L_λ impose

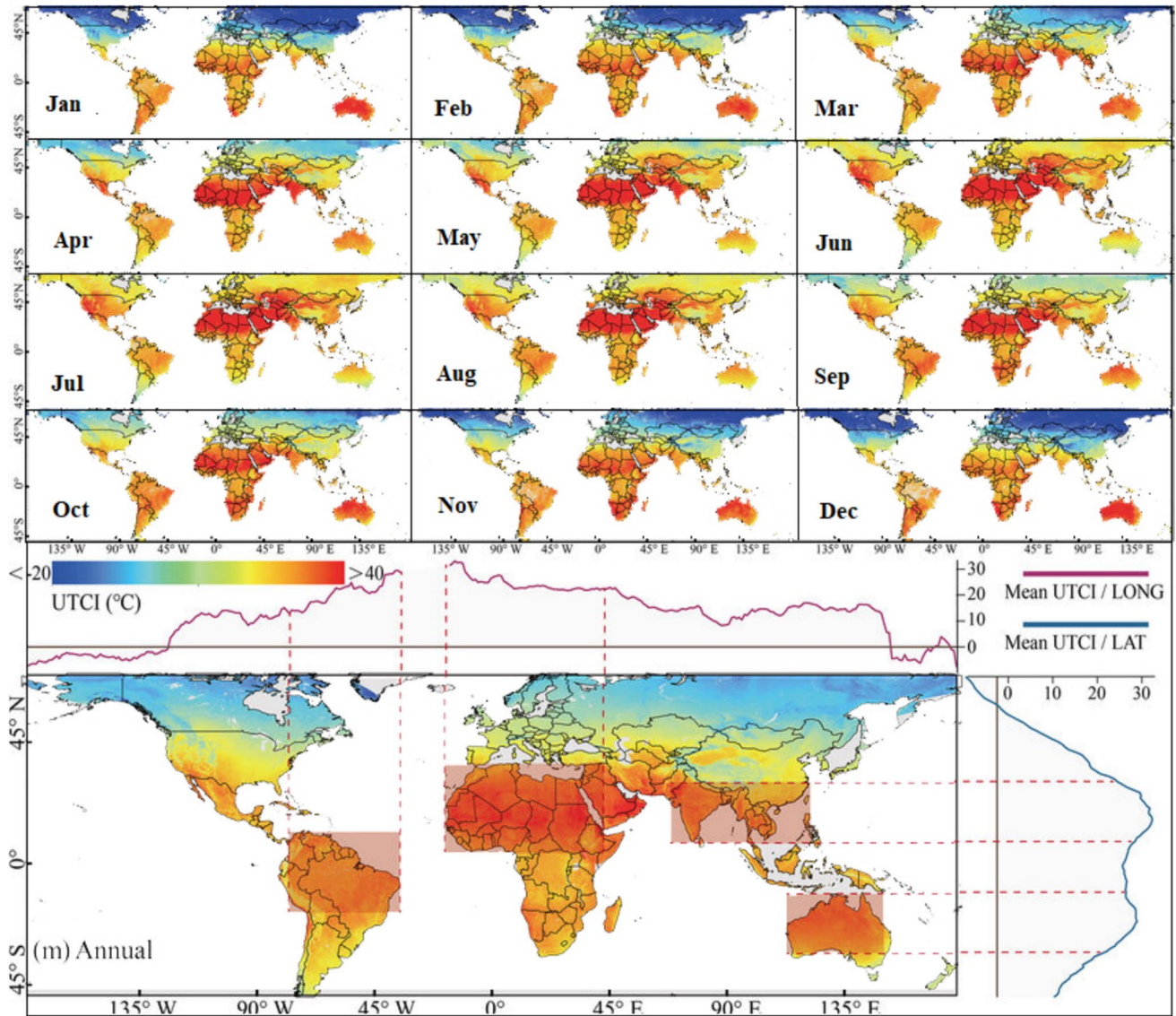


Fig. 9 Monthly and annual distribution of the UTCI (Yang et al. 2024)

spectral radiance. Finally, the LST formula can be applied as follows,

$$LST = \frac{T_{BT}}{1 + \left(\frac{\lambda \cdot BT}{\rho}\right) \cdot \ln \epsilon}$$

where, L_λ Is the wavelength of emitted radiance (typically 10.895 μm for Landsat 9). ρ is Planck's constant (h) * speed of light (c)/Boltzmann constant (σ). ϵ is surface emissivity.

To estimate air temperature, (T_{air}) From LST or MRT, a linear regression model has been used (Fung et al. 2009; Vanos et al. 2021). Where, (a) and (b) are coefficients determined through regression analysis. The coefficient

a represents the slope of the relationship between LST or MRT and air temperature, and b represents the intercept as follows,

$$T_{air} = \begin{cases} a \cdot LST + b \\ a \cdot MRT + b \end{cases}$$

4.4 Relative risk (RR)

The formula for Relative Risk (RR), which is used to estimate the percentage of deaths due to heat, is based on temperature variations and the sensitivity coefficient of various groups:

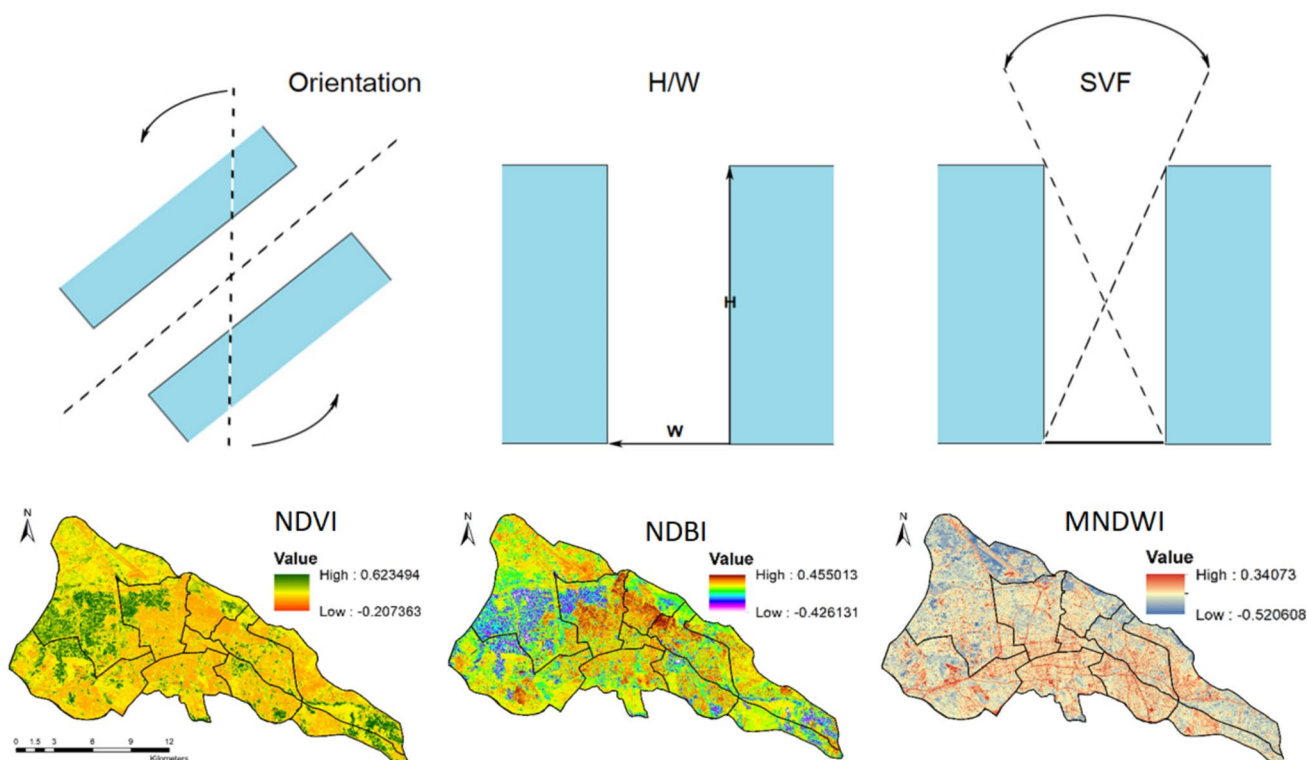


Fig. 10 Urban morphological strategies and their thermal impacts in Tabriz city presented by authors

$$RR = e^{(\beta \cdot \Delta T)}$$

where (RR) represents the Relative Risk (McNutt et al. 2003) (Odame et al. 1597; Fan and Im 2023; Guo et al. 2018). (β) is the sensitivity coefficient derived from epidemiological research (Fig. 12) (Wan et al. 2022; Zhang, et al. 1344; Yang et al. 2019). (ΔT) denotes the temperature change. This formula shows that as temperature (ΔT) rises, the Relative Risk (RR) increases exponentially, with the sensitivity coefficient (β) indicating the degree of this increase.

Figure 12 illustrates the Epidemiological research process on the sensitivity coefficient while Table 16 lists some general sensitivity coefficients (β) for different groups. It should be mentioned that these rates are approximate and may change slightly based on specific local conditions and further detailed epidemiological studies (Schäfer et al. 2024; Thabane, et al. 2013; Calleja-Agius et al. 2021; Vanos et al. 2023).

5 Results of findings

5.1 Overviewing findings

The results and findings have been categorized into climate change and heat-related mortality, representative concentration pathways (RCPs), and urban heat island

(UHI) mitigation strategies. Each section reflects mostly recent findings from peer-reviewed research. Examining the statistics of deaths due to heat stroke between 1980 and 2021 shows that despite the decrease in the death rate from 2020 due to the Covid- 19 pandemic, an increasing trend is evident in the long term as presented in Fig. 13.

5.2 Climate change and heat-related mortality

The analysis reveals significant associations between temperature and health outcomes, emphasizing the need for targeted interventions and public health strategies.

The results of the study revealed significant associations between temperature and health outcomes. Specifically, for every 1 °C rise in mean apparent temperature, overall mortality (all causes) increased by 2.7% (Table 17). Additionally, respiratory morbidity showed a 1.7% increase (Table 18). Among women, respiratory morbidity rose by 2.2%. Furthermore, chronic obstructive pulmonary morbidity increased by 5.4%, and women experienced a substantial 7.5% increase in chronic obstructive pulmonary morbidity. These results underscore the impact of temperature variations on public health, emphasizing the need for targeted interventions and awareness campaigns as follows.

The results of the study encompassing 567 cities show the relative risk of overall cardiovascular mortality

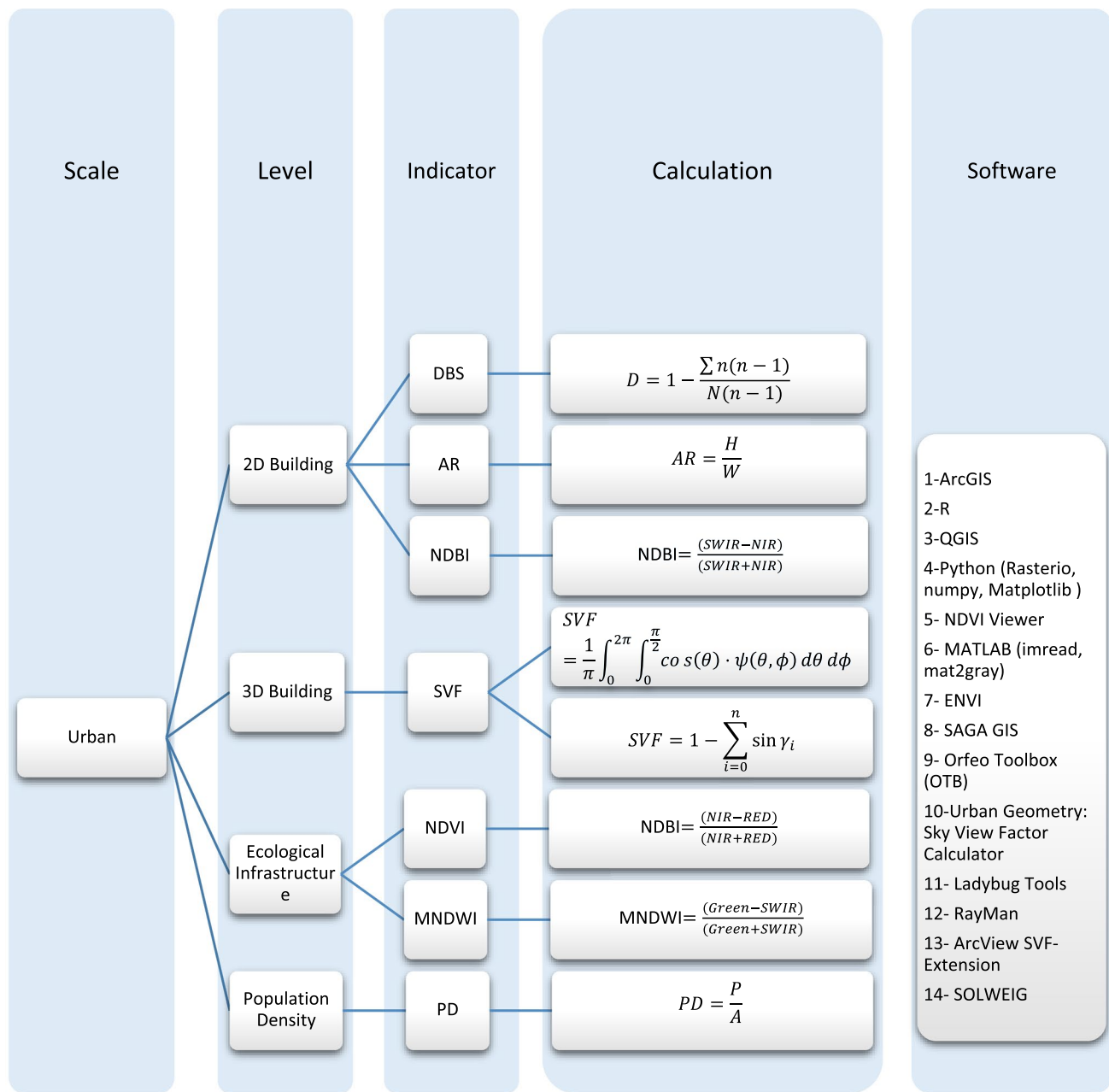


Fig. 11 Morphological indicators and calculation software

increased by 2.1% for every 1 °C rise in temperature (Alahmad 2023). Moreover, air pollution, prevalent in urban areas, exacerbates the impact of global warming on cardiovascular events associated with temperature changes. Specifically, heart failure demonstrated the highest excess deaths proportion during extremely hot and cold days. These findings underscore the critical need to understand temperature-related risks for cardiovascular health and inform public health strategies to mitigate adverse effects (Alahmad 2023). In this multinational sample, exposure to extreme hot and cold temperatures was linked to a greater

risk of cardiovascular death. Specifically: Hot days (above the 97.5 th percentile) accounted for 2.2 excess deaths per 1000 cardiovascular deaths, and cold days (below the 2.5 th percentile) contributed to 9.1 excess deaths per 1000 cardiovascular deaths (Table 18).

5.3 Representative concentration pathways (RCPs)

RCP scenarios delineate varying trajectories of radiative forcing values anticipated by the year 2100. These scenarios are indispensable for climate modeling, facilitating

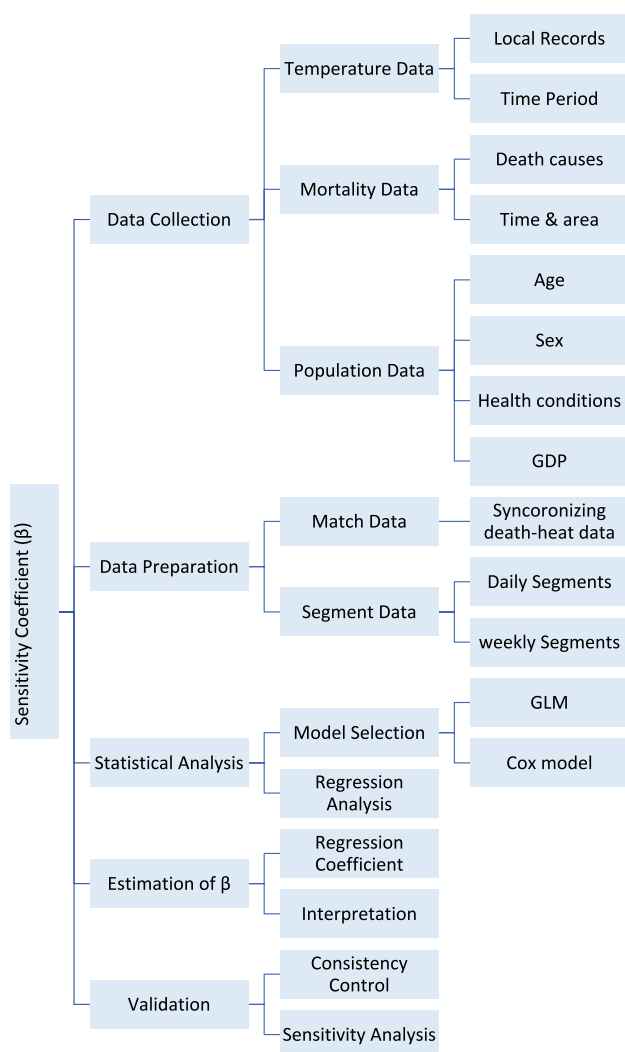


Fig. 12 Epidemiological research process on sensitivity coefficient

polymakers'comprehension of potential future climate conditions and the requisite mitigation efforts.

5.4 Outdoor thermal comfort (OTC) indexes

Regarding OTC indexes, Table 19 summarizes the key aspects of each index, making it easier to compare their purposes, components, and applications.

Different OTC indexes result in different outcomes due to their purposes and components. For example: results of the OTC and UHI management in Chinese districts that have been done by He et al. (2020) disclose that the UHII was

significantly amplified during different heat wave (HW) definitions. Specifically, the maximum UHII increased by 1.3 °C during human-perceived temperature (AppT-HW) events. The daily average UHII saw an increase of 0.8 °C, while the diurnal UHII rose by 0.4 °C. Additionally, the nocturnal UHII experienced a 1.0 °C increase. These temperature differences highlight the extent to which UHII is amplified under various HW definitions, with a particular focus on the impact of human-perceived temperature (AppT-HW).

5.5 Results of urban strategies impacts on mortality

Examining various strategies to mitigate the UHI effect underscores three critical parts including; A) Urban morphology, form, and geometry, B) Green envelops including green roofs, vertical greenery systems, and pedestrian pavements, and C) Building materials and low albedo, D) Medical strategies, and E) Engineering and technological strategies. Also, legislative and successful policies are needed to incorporate these infrastructures into urban planning to decrease ambient temperatures and enhance urban living environments is vital (Ouria and Sevinc 2018; Ouria 2019b; Aflaki, et al. 2017).

5.5.1 Morphological & geometric strategies

Urban formation as a mitigation strategy of UHI does have a potential reduction in temperature by 2–6 °C (Ren et al. 1368; Hedayatnia et al. 2023; Chen and Zheng 2023). Also, 2D/3D urban spatial form indicators show that suitable urban shapes can enhance the urban thermal environment and reduce UHI effects by 1–2 °C (Chen and Zheng 2023; Srivastava et al. 2024). Optimizing urban spatial forms using the genetic algorithm shows that manipulating urban forms based on sky view factor (SVF) can reduce UHI by up to 3 °C while the average UTCI reduced from 31.17 °C to 7.43 °C in summers (Xu et al. 2019). The study revealed the essential of optimizing urban morphologies that cause a remarkable reduction in UTCI (3.74 °C) during summer (Fig. 14). On the other hand, increasing the height-to-width (H/W) ratio can lower ambient temperatures by 1.5–7 °C in hot and dry climates (Hedayatnia et al. 2023). Optimizing urban geometry and increasing greenery strategies can reduce UHI at least by 2–3 °C (Srivastava et al. 2024).

A comparison of the geometrical analysis results highlights the role of orientation, H/W, and SVF. The SVF reduces UHIs 3.5°C averagely ranging between (2–6°C).

Table 16 Sensitivity coefficients (β) for different groups

Group	Age Groups		Sex Groups		GDP Groups	
	Children and Elderly	Adults	Females	Males	Low	High
(β)	0.02—0.03	0.01—0.02	0.015—0.025	0.01—0.02	0.03—0.04	% 1.% 2—0.02

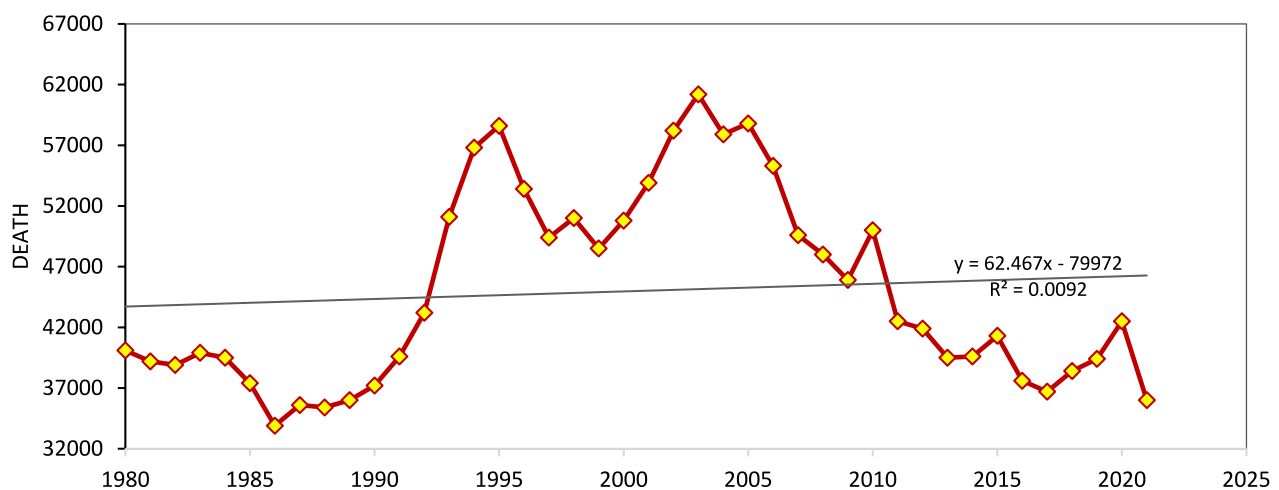


Fig. 13 Heat (hot and cold exposure) causes of death, World, 2021 (IHME 2021)

Table 17 The impact of temperature variations on public health

Effect	Percentage Increase
Overall mortality (all causes)	2.7%
Respiratory morbidity	1.7%
Respiratory morbidity (women)	2.2%
Chronic obstructive pulmonary morbidity	5.4%

Table 18 The risk of cardiovascular deaths exposure to extreme hot and cold temperatures

Temperature Category	Excess Deaths per 1000 Cardiovascular Deaths
Hot days	2.2
Cold days	9.1

The appropriate H/W ratio reduces the temperature by more than 4°C on average. The appropriate orientation of roofs and blocks causes mitigating (2–3.5°C). Regarding different climates, the geometrical strategies are more decisive in the Mediterranean climate (Fig. 14).

The SVF immediately cools the urban spaces due to the shading but its storage heat on urban elements heats the temperature during the night. A lower rate of SVF (0.2) causes a higher rate of UHI (+ 2°C) at night (Fig. 15).

Regarding diurnal impacts, the SVF impacts different human groups with heat-related mortality varying from 2 to 10%. The results show that SVF > 0.7 is safe for most groups. The worst scenario happens under SVF < 0.3 for countries with lower GDP. The mortality rate of elderly (people > 65) records > 8% experiencing SVF < 0.2 (Fig. 16).

5.5.2 Humidity & mortality

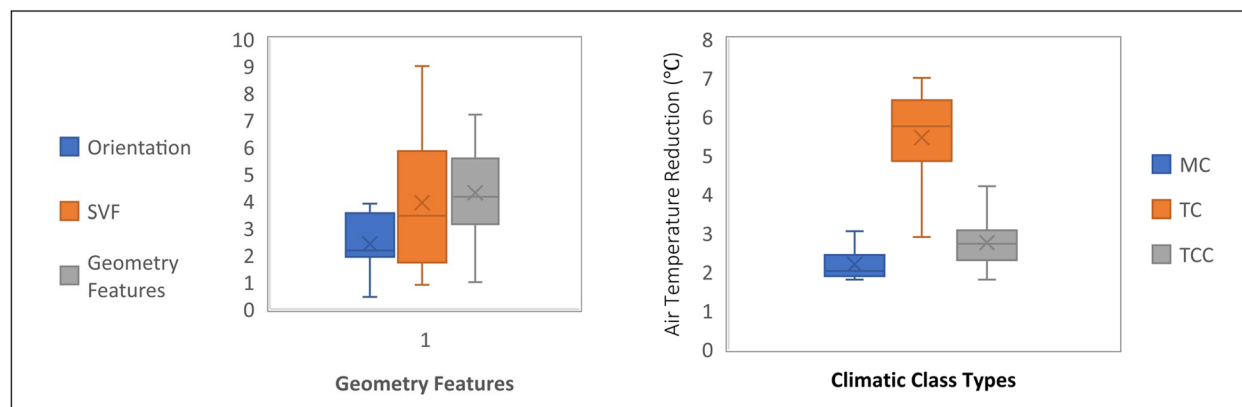
The analysis of RH and heat-related mortalities in various regions reveals significant associations between humidity levels and death rates. In Chinese cities, studies show that RH contributes to notable increases in all-cause and cardiovascular mortality rates, with Beijing's RH-attributable all-cause mortality at 6.80% and cardiovascular deaths at 12.48% (Mei, et al. 2023; Deng, et al. 2023). European cities also exhibit similar trends, with Milan experiencing a 33.6% increase in mortality during heat waves and Mediterranean cities showing a 21.8% increase (D. 2010). In American cities, high RH exacerbates mortality risks, with Atlanta's mortality rate rising by 15%, Philadelphia by 20%, and Phoenix by 25% (Stone et al. 2014). These findings underscore the importance of considering both temperature and humidity in public health strategies to effectively reduce weather-related mortalities. By incorporating RH into heat stress indicators, cities can enhance their predictive power for heat-related mortality and implement more effective mitigation strategies (Fig. 17).

5.5.3 Greenery & NDVI strategies

The (GI) literature reveals that the surface temperatures can be reduced by up to 1–4 °C (Balany et al. 2020). In terms of OTC and UHIs, it has focused mostly on trees rather than green roofs, green walls, and parks while they reduced the ambient temperature by 1–4 °C through shade and evapotranspiration (Balany et al. 2020; Wong et al. 2021), (Wong, et al. 2010). Also, greenery spaces can reduce peak surface temperatures by 2–9 °C for parks and up to 17 °C for green roofs and walls, but optimizing the design process was crucial for maximizing mitigation

Table 19 Purposes, components, and applications of OTC indexes

Index	Purpose	Components	Application
Wind Chill Index (WCI)	Measures perceived decrease in temperature due to wind	Temperature, wind speed	Cold climates to estimate frostbite and hypothermia risk
Wet Bulb Globe Temperature (WBGT)	Measures heat stress in direct sunlight	Temperature, humidity, wind speed, sun angle, cloud cover	Occupational health, sports, military activities
Humidex	Indicates perceived temperature combining air temperature and humidity	Temperature, relative humidity	Public Weather Forecasting in Canada
Heat Index (HI)	Measures the combined effect of temperature and humidity on perceived temperature	Temperature, relative humidity	Public heat stress advisories in the United States
Apparent Temperature (AT)/ Human Perceived Temperature (HPT)	Reflects how hot it feels considering temperature, humidity, and wind speed	Temperature, humidity, wind speed	General human perception of weather conditions
Standard Effective Temperature (SET)	Assesses thermal comfort with multiple factors	Temperature, humidity, air movement, radiant temperature	Building design, HVAC system planning
Physiological Equivalent Temperature (PET)	Measures thermal comfort by integrating meteorological and physiological factors	Temperature, radiant temperature, air velocity, humidity	Urban planning, climatology
Specific Meteorological Variables (SPMV)	Custom indices based on specific research needs	Varies based on the study's requirements	Tailored to agriculture, climatology, health research
Universal Thermal Climate Index (UTCI)	Assesses the outdoor thermal environment's effect on health and comfort	Temperature, wind speed, humidity, radiation	Global use in urban planning, public health, and climate impact studies

**Fig. 14** Impacts of Geometry Features in Temperature (°C) Reduction with different climates

benefits (Wong et al. 2021). A 20% reduction in surface temperatures is observed by effective integration, innovation, and evaluation mechanisms for UHI management while an Asian project reported a 15–30% reduction in ambient temperatures regarding nature-based solutions (NBS) for UHIs (Almashhour et al. 2024; Ramakreshnan and Aghamohammadi 2024) (Fig. 18).

The UHI changes by specific NDVI amounts (0.1) in various cities and climates (summer week focus) are variable but highlight an indirect relation with temperature. Increasing each 0.1 in NDVI value causes decreasing air temperature from (0.5 °C) to (4 °C) but on average it causes 1 to 2 °C

mitigation in temperature. Arid climates recorded a cooler impact (− 2 °C) while temperate climates were recorded (− 1 °C) on average (Fig. 19).

The NDVI results show that elderly people > 65 and women mortality in countries with low GDP in Mediterranean, tropical, and arid climates are highly affected. Regarding temperate climates only 2% of male adult mortality is mitigated by each 0.1 change in NDVI in countries with high GDP. On the other hand, the mortality of groups with low GDP is mitigated by 6% to 10% in all climates. Also, the mortality of elderly people is mitigated by 10% in tropical climates (Fig. 20).

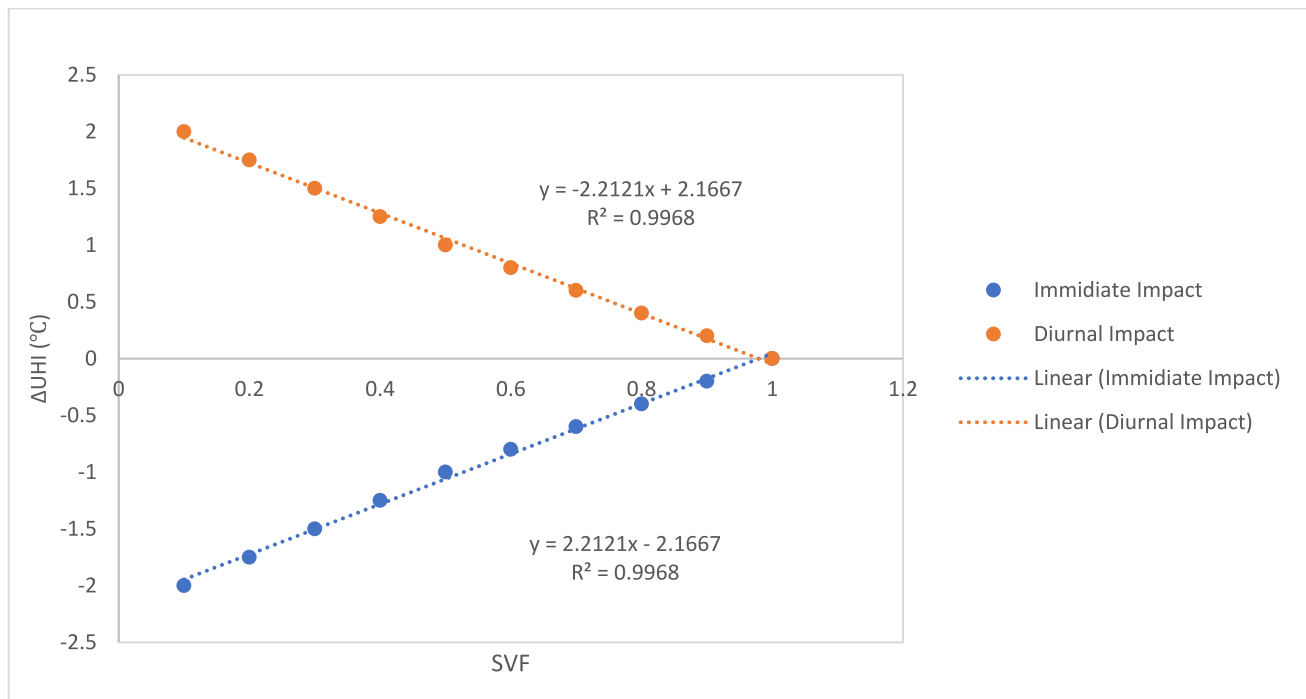


Fig. 15 SVF impacts on UHI

The heat-resilient infrastructure proposes a framework regarding sustainable initiatives presented by Cui et al. (2024). The heat-resilient framework consists of structural and non-structural measures. However, the sustainable initiatives have presented focusing on the greenery infrastructure (GI) clearly (Fig. 21).

Crucially, the cooling components in sustainable initiatives (such as green buildings, sponge cities, forest cities, garden cities, low-carbon eco-cities, and climate-adaptive cities) should focus on overcoming or at least reducing the economic, social, and policy obstacles to implementing heat mitigation and adaptation measures. While greenery strategies significantly contribute to reducing surface temperatures, technological interventions such as photovoltaic panels and air-source heat pumps present new challenges in balancing temperature regulation (Ouria et al. 2025; Azami 2014). These emerging technologies require careful integration into urban planning to maximize benefits while minimizing adverse effects.

5.5.4 Building materials, NDBI, and low albedo strategies

The results of materials and NDBI strategies analyzed into microclimate scale for rooftops, pavements, and PCMs show a remarkable impact of PCMs and reflective pavements on surface temperature (-6.5°C to -8°C) on average. The use of these materials mitigates temperature rates in all microclimates (Fig. 22).

The UHI changes by specific NDBI amounts (0.1) in various cities and climates (summer week focus) are variable. NDBI does have a direct relation with UHI. Razing each 0.1 in NDBI value causes increasing air temperature from (0.5°C) to (3.5°C) but on average it causes increasing 1.5 to 2°C in temperature. Temperate climates recorded a higher impact ($+2^{\circ}\text{C}$) while tropical and Mediterranean climates were recorded ($+1^{\circ}\text{C}$) raising on average (Fig. 23).

In terms of NDBI impacts on the mortality of different groups, the results highlight the vulnerability of elderly people (7%) and women (6%) in humid and subtropical climates. The most effective group due to NDBI is low-income groups in all climates. However, the mortality of this group hit a record (10%) in humid and subtropical climates (Fig. 24).

5.5.5 Medical strategies

The results of the medical and emergency strategies in urban spaces show a direct impact on mitigating heat-related mortalities by appropriate education and warning systems (-10% to -25%), and services in cooling centers (-30% to -15%) during heat storms (Fig. 25).

5.5.6 Technological & engineering strategies

The results of technological and engineering strategies analysis show diverse outcomes regarding different scales. The

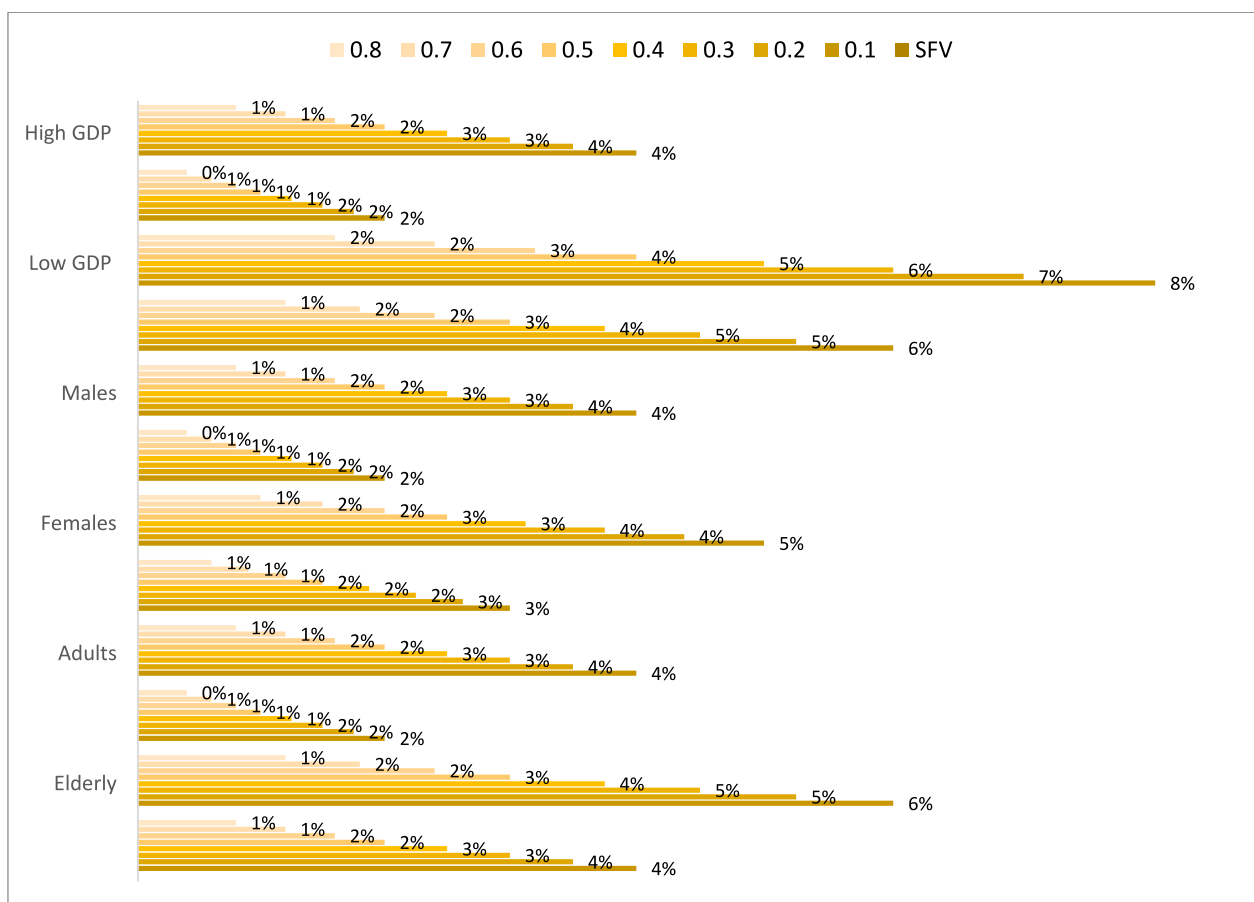


Fig. 16 SFV impacts on Mortality Rate presented by authors using the formula for Relative Risk (RR) and Sensitivity coefficients (β) for different groups adopted from field survey statistics and literature review

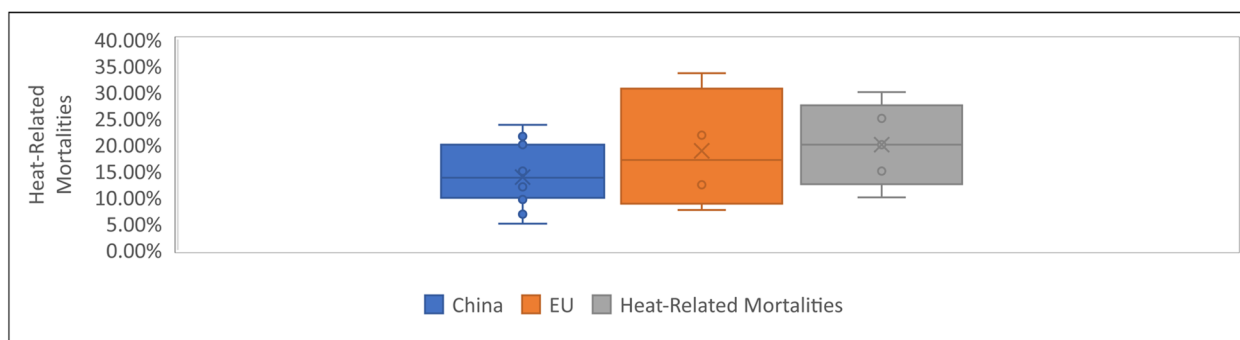


Fig. 17 RH impacts on heat-related mortalities

electrification of the transportation systems shows 0.5 °C mitigation in UHIs in mesoscale. However, the use of PVs does have a complex impact on UHIs. The PVs mitigate the UHIs by decarbonization in general while the arrays increase the local points (0.6°C – 0.9°C). Also, the AAHPs increase UHI by 0.5°C (Fig. 26).

The results of heat-related mortality due to emerging technologies and electrification of the cities, only the EVs mitigate the mortality rates (– 1%) due to UHI mitigation (Fig. 27). On the other hand, the AAHPs and implementing PV panels increase the potential of heat-related-mortality rates (+ 1%).

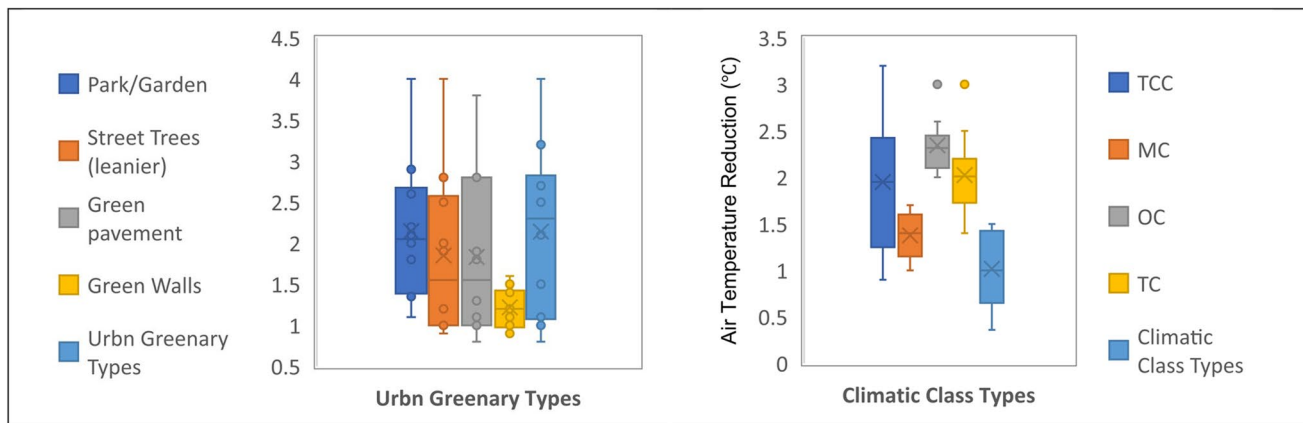
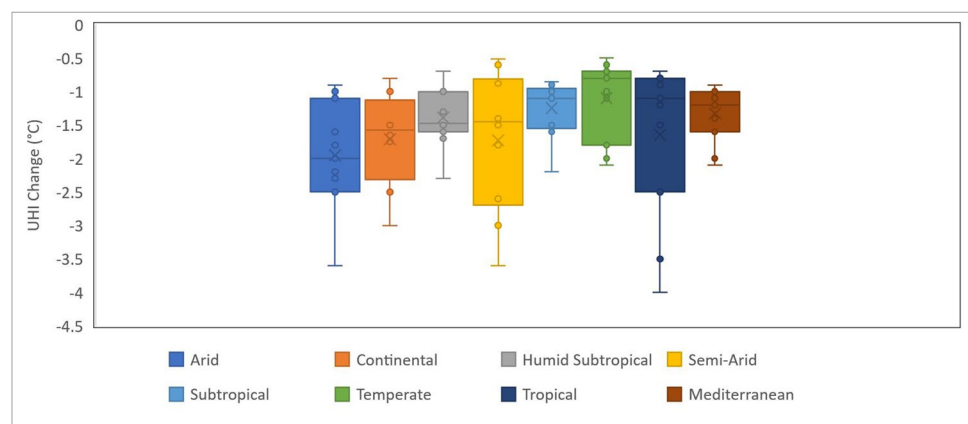


Fig. 18 Impacts of GI strategies in Air Temperature (°C) Reduction with different climates

Fig. 19 UHI affection per 0.1 variation in NDVI value in different climates regarding different locations



The role of emerging technologies such as PV panels and AAHPs demonstrates the interplay between sustainable urban strategies and heat-related mortality mitigation. Although localized heating effects are observed, there are net benefits through their integration with green infrastructure strategies, contributing to a balanced approach aligned with the theoretical framework.

6 Summary of findings and discussions

6.1 Overview of findings

The results and findings have been categorized into climate change and heat-related mortality, representative concentration pathways (RCPs), and sustainable mitigation strategies with a special focus on urban heat island (UHI). Each section

reflects mostly recent findings from peer-reviewed research. Examining the statistics of deaths due to heat stroke between 1980 and 2021 shows that despite the decrease in the death rate from 2020 due to the Covid- 19 pandemic, an increasing trend is evident in the long term as presented in Fig. 13.

6.2 Climate change and heat-related mortality

The analysis reveals significant associations between temperature, humidity, and health outcomes, emphasizing the need for targeted interventions and public health strategies. The quantitative analyses demonstrate that every 1 °C rise in mean apparent temperature increases overall mortality by 2.7%, with notable impacts on respiratory and cardiovascular morbidity (Alahmad 2023) while (A. M. 2021) reported a nearly 70% increase in heat-related mortality among individuals over 65 years of age in the past two decades.

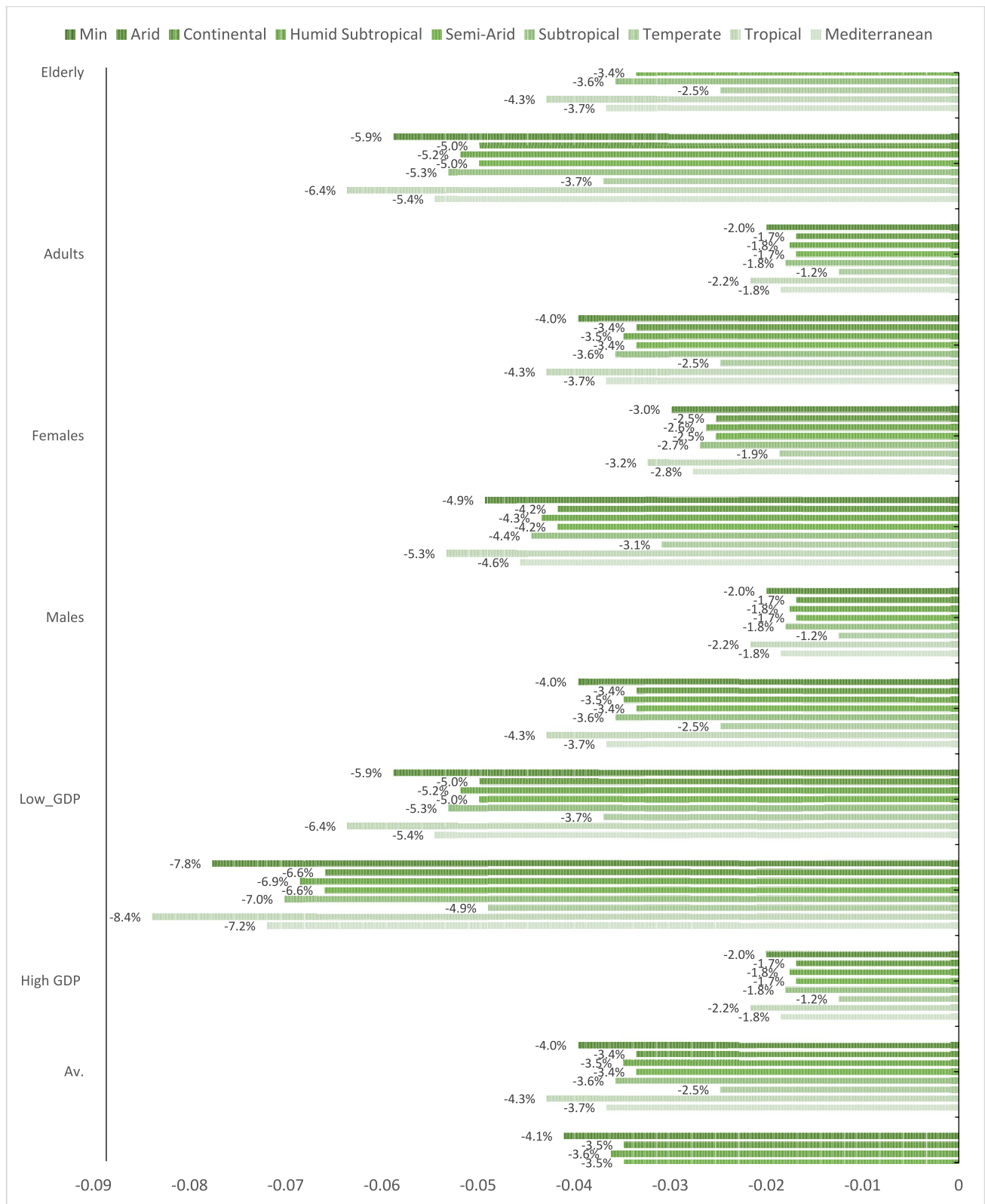
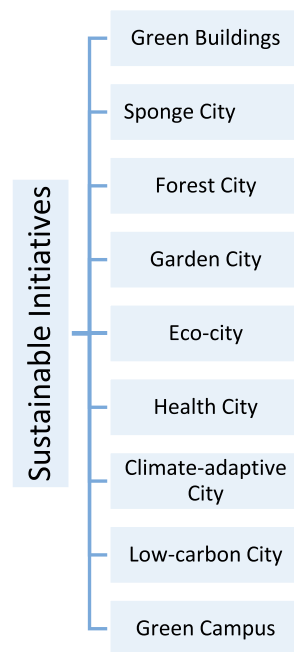


Fig. 20 UHI affection per 0.1 variation in NDVI value in different climates regarding different human groups

Fig. 21 Sustainable initiatives regarding GI (Cui et al. 2024)



6.3 Representative concentration pathways (RCPs)

RCP scenarios delineate varying trajectories of radiative forcing values anticipated by the year 2100. These scenarios are indispensable for climate modeling, facilitating

policymakers' comprehension of potential future climate conditions and the requisite mitigation efforts.

Regarding RCPs (Rohat, et al. 2021) highlighted the importance of using RCP scenarios for planning and mitigation strategies to reduce heat-related mortalities while (Santamouris 2022) emphasized the need for accurate climate modeling to understand future impacts and inform effective interventions.

6.4 Urban heat island (UHI) mitigation strategies

Findings related to NDVI, UHI reduction, and thermal comfort indices substantiate the framework's focus on sustainable urban strategies as multifaceted solutions to mitigate heat-related mortalities. The results highlight the critical need for an integrated approach, combining ecological, technological, and health interventions to address the challenges posed by extreme urban heat. Examining various strategies to mitigate the UHI effect underscores three critical parts:

- Urban morphology, form, and geometry:** Urban formation as a mitigation strategy for UHI can reduce temperatures by 2–6 °C, depending on the region and specific strategies implemented. Subsequently, (Xu et al. 2019) demonstrated that optimizing urban geometry can significantly reduce UHI effects, supporting this study's findings.

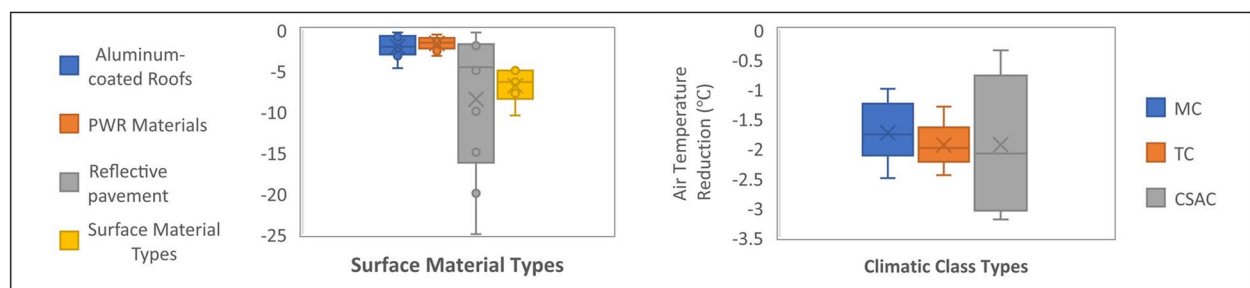


Fig. 22 Impacts of materials and low albedo strategies in Temperature Reduction with different climates

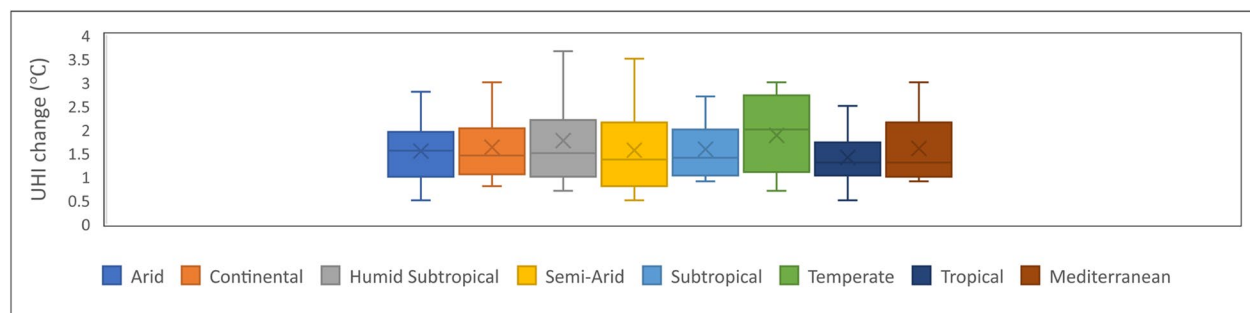


Fig. 23 UHI Changes per 0.1 variation in NDBI value in different climates

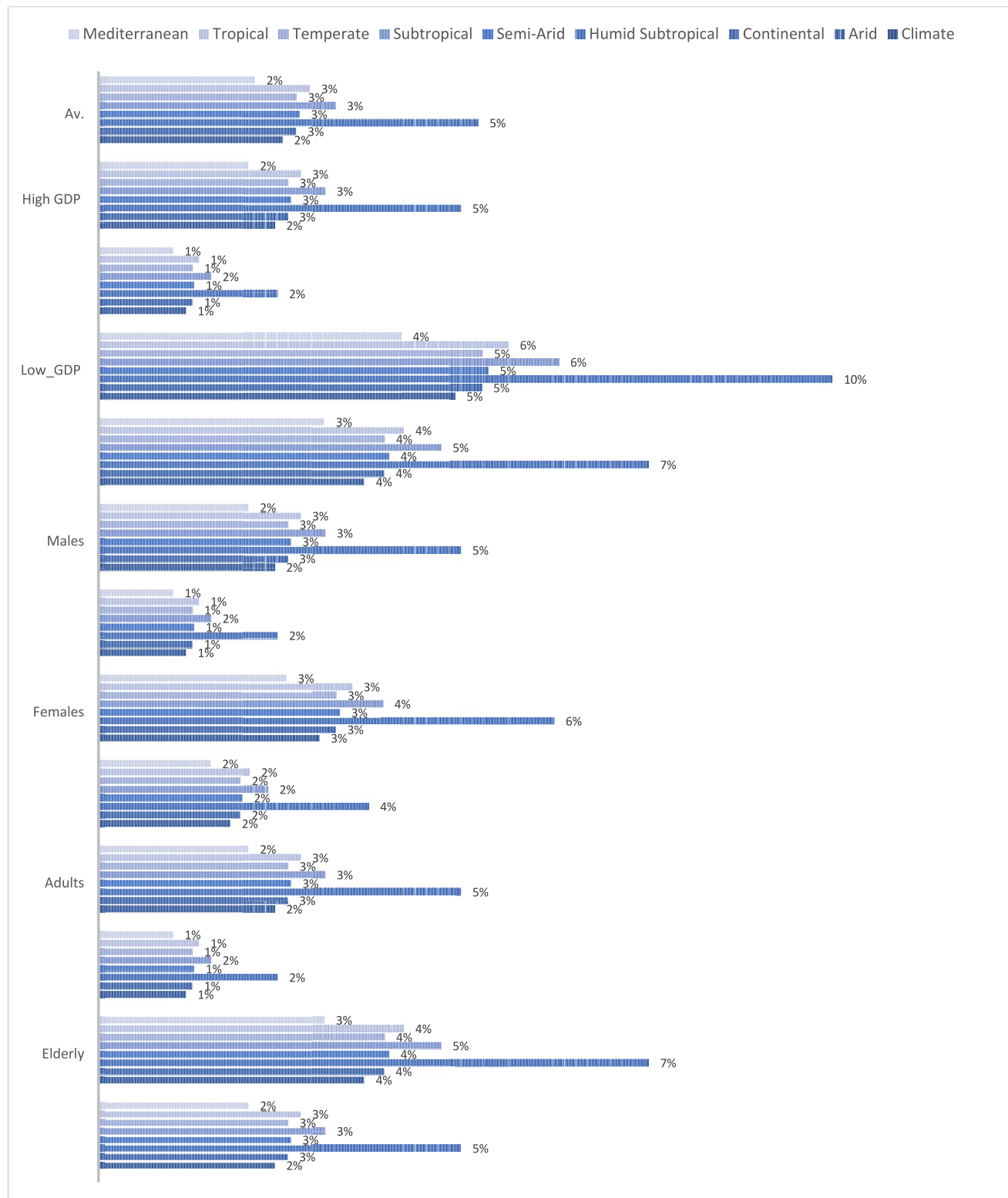


Fig. 24 UHI Changes per 0.1 variation in NDBI value in different groups

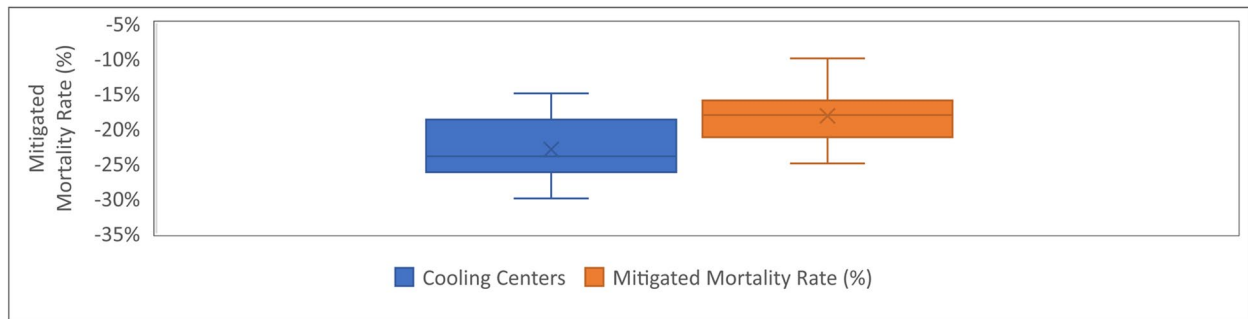


Fig. 25 Impacts of Medical Strategies on Mortality Reduction

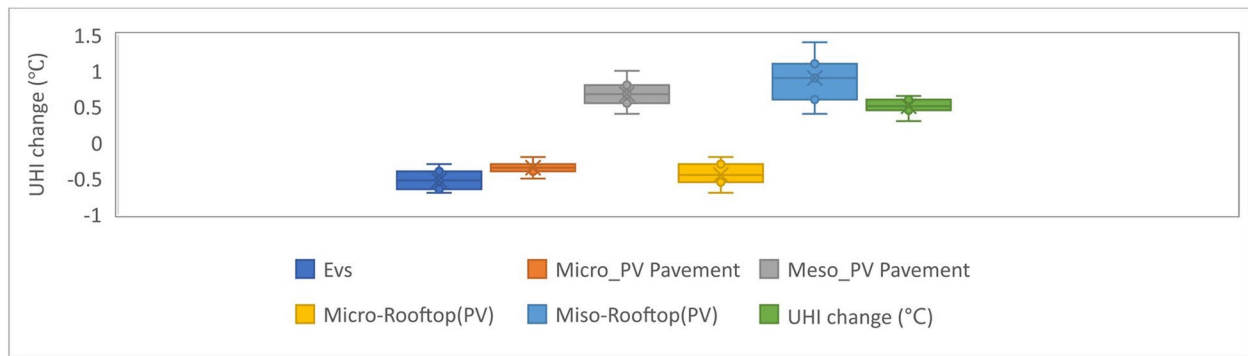


Fig. 26 Impacts of Technological & Engineering Strategies in Temperature (°C)

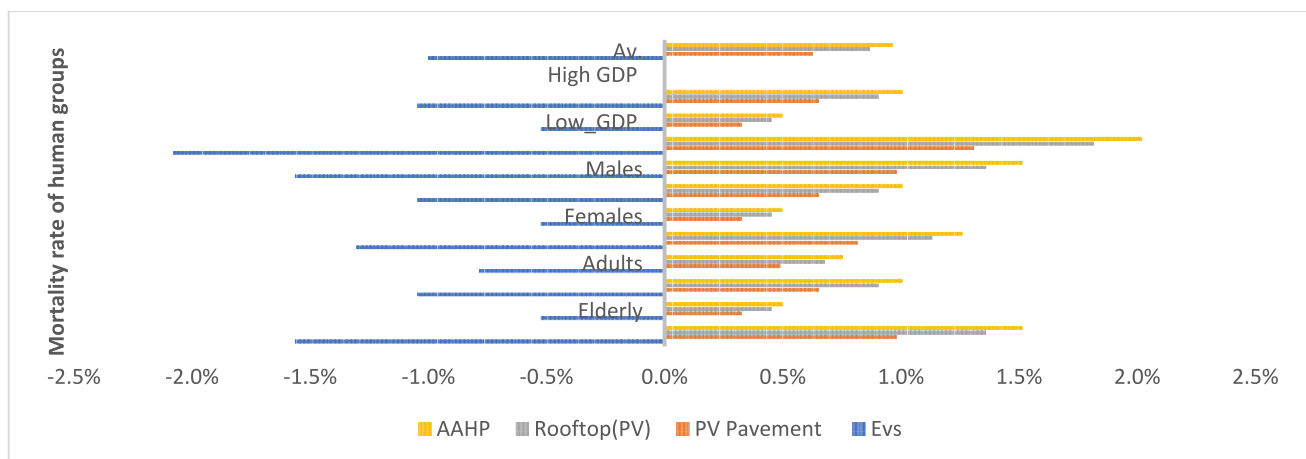


Fig. 27 Impacts of Emerging Technologies on Mortality Reduction

- **Green envelopes:** Integrating green roofs, vertical greenery systems, and pedestrian pavements can significantly reduce surface temperatures and mitigate UHIs that are highlighted by Wong et al. (2021). Also, (Balany et al. 2020) highlighted shade and evapotranspiration reduced the ambient temperature by 1–4 °C.

The results indicating that green infrastructure reduces surface temperatures by 1–4 °C align closely with the theoretical framework's emphasis on green solutions as pivotal components of Sustainable Urban Strategies. These findings underscore the critical role of vegetation not only in mitigating UHIs, but also in enhancing overall Outdoor Thermal

Comfort (OTC) indices, as outlined in the study's framework. The reduction in UHI intensity achieved through urban morphology and GI strategies validates the framework's emphasis on combining spatial and ecological interventions to mitigate heat-related mortality rates and improve thermal comfort indices.

Utilizing reflective pavements, cool materials, and PCM strategies can significantly reduce surface temperatures. The effectiveness of reflective materials emphasized by Santamouris (2013) in reducing heat absorption, is consistent with this study's findings. Also, (Akbari and Matthews 2012) demonstrated significant reductions in heat absorption with the use of reflective materials.

Building materials and low albedo

- **Medical strategies:** Effective warning systems and cooling centers can substantially reduce heat-related mortalities during extreme heat events.
- **Engineering and technological strategies:** Technological interventions, such as the electrification of transportation systems and the use of PV panels, have varying impacts on UHIs and heat-related mortality rates.

6.5 Practical implications and feasibility

The observed decrease in heat-related mortalities through NDVI enhancements presents a compelling case for policymakers to prioritize urban greening initiatives, particularly in low-income regions where potential mortality reductions are most pronounced. Implementing these strategies requires coordinated efforts from policymakers, urban planners, and public health officials:

- **Policy Decisions:** Promote sustainable building practices and urban greening initiatives to create more resilient cities.
- **Urban Planning:** Design buildings and urban spaces to maximize shade and airflow, reducing the UHI effect.
- **Public Health Initiatives:** Develop early warning systems, cooling centers, and public education campaigns to protect vulnerable populations during heat waves. Provide shelter support to the most vulnerable population in extreme weather situations.
- **Technological Adaptations:** Adopt renewable energy technologies and carefully implement PV panels and AAHPs by conducting thorough impact assessments.
- **Community Engagement:** Involve community members in planning and implementing heat adaptation measures to ensure they address specific local needs and enhance community resilience.

7 Conclusions and recommendations

These strategies demonstrate measurable reductions in urban heat islands, providing critical benefits in reducing heat-related mortalities and improving thermal comfort for the population in general, particularly for vulnerable populations.

This research validates the significance of thermal comfort indices and UHI mitigation strategies within urban planning frameworks, providing empirical evidence for their effectiveness in reducing heat-related mortalities. Integrating greenery into urban infrastructure is not just an ecological necessity but a public health imperative, with measurable benefits for health and quality of life improvement, leading to large social and economic benefits for the population.

7.1 Conclusions

The outcomes of this study extend the theoretical framework by demonstrating how the integration of urban morphology, health strategies, and emerging technologies can effectively address heat-related mortalities and enhance outdoor thermal comfort. These findings underscore the importance of adapting the framework to diverse socioeconomic and climatic conditions.

- **Heat-Related Mortality and Urban Heat Island Effects:** The quantitative analyses demonstrate that every 1 °C rise in mean apparent temperature increases overall mortality by 2.7%, with notable impacts on respiratory and cardiovascular morbidity. Urban areas, particularly those with high UHI effects, are especially prone to heat stress, emphasizing the need for targeted mitigation efforts.
- **Vulnerable Populations:** The elderly, low-income communities and those with pre-existing health conditions are at higher risk during extreme heat events. Relative humidity significantly contributes to increased mortality rates in regions such as Beijing (6.80% all-cause mortality) and Milan (33.6% increase during heat waves).
- **Integrated Mitigation Strategies:** Combining various measures, such as green infrastructure, reflective materials, and public health initiatives, has been shown to lower heat-related deaths. Increasing green spaces can reduce surface temperatures by up to 4 °C, while reflective materials can decrease heat absorption by 20–30%.

7.2 Recommendations

While this study provides robust insights into urban heat mitigation strategies, future research could explore the long-term effects of electrification technologies, such as

optimized urban design, PV panels, and AAHPs, on meso-scale urban climates. Further investigations are needed to quantify the combined impacts of technological and green interventions in tropical and arid climates, where mortality risks remain disproportionately high.

The integration of sustainable building materials and urban morphology adjustments offers cost-effective solutions for reducing temperatures and enhancing thermal comfort in densely populated cities. Urban planners and policymakers should prioritize these strategies, ensuring their adaptation to local climatic and socio-economic conditions.

7.2.1 Policy decisions

- **Promote Sustainable Building Practices:** Implement policies that incentivize green building practices, such as using reflective materials and incorporating green infrastructure into urban designs.
- **Encourage Urban Greening Initiatives:** Provide grants and subsidies for urban greening projects, including the development of parks, green roofs, and vertical greenery systems.

7.2.2 Urban planning

- **Optimize Building Orientation and Design:** Design buildings and urban spaces to maximize shade and airflow, reducing the UHI effect.
- **Integrate Green Spaces:** Increase the number of parks and green spaces to provide natural cooling and enhance thermal comfort in urban areas.

7.2.3 Public health initiatives

- **Develop Early Warning Systems:** Implement early warning systems to alert the public about upcoming heat waves and provide guidance on protective measures.
- **Establish Cooling Centers:** Create accessible cooling centers in urban areas to provide relief during extreme heat events, particularly for vulnerable populations.
- **Conduct Public Education Campaigns:** Raise awareness about the dangers of heat stress, the importance of hydration, and recognizing heat-related illnesses.

7.2.4 Technological adaptations

- **Adopt Renewable Energy Technologies:** Promote the use of renewable energy sources, such as solar and wind, to reduce carbon emissions and mitigate the UHI effect.
- **Optimization of Implementation of Solar PV Panels and AAHPs:** Balance the benefits of PV panels and

AAHPs with their potential to increase localized temperatures by conducting thorough impact assessments.

7.2.5 Community engagement

- **Engage Local Communities:** Involve community members in planning and implementing heat adaptation measures to ensure they address specific local needs and enhance community resilience.
- **Support Vulnerable Populations:** Provide targeted support and resources to elderly, low-income, and health-compromised individuals to reduce their risk during extreme weather events.

Author contribution A: writing—original draft preparation; A, B & E: conceptualization, methodology, data collection and analysis, interpretation of results, reviewing and editing. D & E: supervision, reviewing and editing, validation and approval. C.E.: reviewing and editing, validation and approval. C.D.: reviewing and editing. E.: supervision.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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