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Evaluating urban heat island mitigation strategies through coupled UHI and building energy modeling

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A R T I C L E I N F O

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A B S T R A C T

The Urban Heat Island (UHI) effect, exacerbated by urban expansion and climate change, poses significant challenges for sustainable urban development, public health, and environmental resilience. Despite growing research, there is a lack of consensus on the most effective strategies and modeling approaches to accurately assess and mitigate UHI effects, particularly in diverse climatic regions. This comprehensive literature review aims to classify and analyze various methodologies, tools, and models used to address UHI, providing a foundational understanding and identifying knowledge gaps. By examining over 100 scientific studies, the review identifies integrated modeling approaches combining urban climate models (UCM) and building energy models (BEM) to enhance thermal comfort and energy efficiency. It explores the efficacy of strategies such as green roofs, high-albedo materials, and urban vegetation in reducing UHI intensity across different climatic regions. The review also emphasizes the importance of detailed urban morphology and meteorological data in improving UHI simulation accuracy. Future research directions include advancing UHI modeling techniques, validating simulation tools through empirical data, and exploring the impact of various mitigation strategies on urban thermal comfort and energy consumption. This literature review offers a comprehensive analysis of current UHI research, providing insights into effective mitigation strategies and modeling approaches to address the UHI effect.

1. Introduction

Urban heat islands (UHIs) represent a significant environmental challenge that exacerbates the thermal environment within urban areas, leading to higher temperatures compared to surrounding rural/suburban areas. This phenomenon not only affects energy consumption patterns due to increased air conditioning demand but also has serious impacts on public health, air quality, and the overall urban ecology. As urban populations continue to expand and climate change intensifies, the need for effective UHI mitigation strategies becomes paramount.

The 21st century has witnessed an unprecedented surge in urbanization. The growth of urban populations has been rapid, increasing by approximately 4.6 times in the past 70 years. By 2050, it is expected that urban populations will reach 6.4 billion, which amounts to 68% of the world's population [1]. According to Brozovsky et al. [2], climate change, urbanization, population growth, and their environmental consequences are some of the most pressing challenges facing humanity in the 21st century. Besides new economic, managerial and social challenges associated with urbanization and growing cities, a deformed energy budget pulls them toward a warmer climate condition and a rise in temperatures in urban areas (UHI) [3,4]. This phenomenon (UHI) must be more tangible and considered by architects and urban planners to create more sustainable and livable cities for future generations. By prioritizing UHI mitigation strategies in our urban design efforts—such as using surface materials that reflect more solar radiation, increasing greenery, and reducing anthropogenic heat—the destructive cycle of

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UHI can be broken and healthier environments will be created for all.

Acronyms	
AT	Air Temperature
BEM	Building Energy Model
CIM	Canopy Interface Model
EPW	EnergyPlus Weather Data
HVAC	Heating, Cooling and Air Conditioning
LST	Land Surface Temperature
MRT	Mean Radiant Temperature
SVF	Sky View Factor
TMY	Typical Meteorological Year
UCL	Urban Canopy Layer
UCM	Urban Climate Model
UHI	Urban Heat Island
USWD	Urban Specific Weather Dataset
UTCI	The Universal Thermal Climate Index
UWG	Urban Weather Generator

Integrated modeling approaches have emerged as powerful tools for understanding and addressing the multifaceted nature of UHIs. By synthesizing data from various domains, including meteorology, urban morphology, materials science, and human behavior, these models offer nuanced insights into the complex dynamics that contribute to urban heat accumulation. Crucially, they also provide a means for evaluating the potential efficacy of various mitigation strategies, e.g. the implementation of green infrastructure and the adoption of high-albedo materials in construction.

Nevertheless, this method faces several challenges and limitations. Urban heat island (UHI) phenomena occur at various scales, necessitating models that capture both macro-level trends and micro-level details. Understanding the seasonal and diurnal variations in UHI intensity across different seasons and throughout the day presents a significant challenge. Obtaining accurate and comprehensive urban datasets—covering features like building geometry, land cover, and surface materials—remains an ongoing struggle. Validating integrated UHI models requires extensive data sets and observational studies to ensure accurate representation of real-world conditions and dynamics. Additionally, addressing uncertainty and sensitivity in these models, considering input data and parameters, is a complex task. Finally, integrating UHI models with other domains (such as air quality, hydrology, and energy) necessitates understanding intricate interactions and developing coupled models that account for feedback loops [5–7]. Despite several research studies having been conducted, only a few have explored the coupling of UHI modeling and building energy models.

This study aims to propose a more comprehensive and detailed state-of-the-art review, presenting the most updated research trends on integrated modeling approaches for UHI mitigation. It summarizes and compares different models and software, examining how coupling Urban Climate Models (UCM) and Building Energy Models (BEM) enhances the reliability of simulation results, providing a more precise urban weather dataset. The research introduces a novel framework for integrated UHI and building energy modeling, leveraging advanced machine learning techniques to improve accuracy and scalability. This approach offers insights into the most effective strategies and tools for urban planners, policymakers, and sustainability advocates.

The work presents an up-to-date and in-depth comparative analysis of each approach, evaluating their unique insights and applications to assess their applicability in real-world scenarios. This analysis is essential for informing stakeholders on how to couple UHI modeling and building energy models based on input parameters and specific simulation goals. The findings are particularly useful for optimizing energy efficiency and reducing the impact of UHIs, serving as a valuable resource for implementing sustainable and resilient urban development strategies. This research provides a thorough examination of UHIs from multiple perspectives, integrating advanced modeling techniques and offering practical recommendations for addressing UHI challenges through urban planning, building design, and community engagement strategies.

The work is structured as follows: after the introduction, we delve into mitigation strategies (Segment 2), explore both uncontrollable and controllable variables that cause UHI and analyze the impact of UHI on human health and the climate, and realize the urgent need for action about UHI (Segment 3). (Segment 4) provides a comprehensive overview of the Urban Canopy Model (UCM), an integrated approach to UHI modeling. It includes a critical review and comparison of related software across various spatial scales. Subsequently, (Segment 5) delves into the methodology of coupling UCM with the Building Energy Model (BEM) to generate the Urban Specific Weather Dataset (USWD). In the subsequent section (Segment 6), we discuss research limitations, followed by a summary of findings and conclusions in Segment 7. Fig. 1 depicts a graphical abstract of the review.

2. UHI strategies history and current status

The review approach comprised searching in different databases, including Scopus and Web of Science. The initial search results identified over 691 articles. After applying limitations and exclusion criteria, this number was reduced to 217 articles that met the inclusion and exclusion criteria. The exclusion criteria included articles that were irrelevant based on the title and abstract of the study, as well as those that did not focus on the coupling of UHI modeling and building energy models. Upon further in-depth review, 113 high-quality articles were selected for analysis. The search and refinement process in this systematic review followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The flowchart of the PRISMA process is depicted in Fig. 2.

Fig. 3 shows the temporal distribution of the studies.

While UHIs pose risks to residents and urban sustainability during summer and heat waves, they offer notable benefits in winter and cold climates [8]. According to Fan et al., [9] in severe-cold-region cities in China, the UHI effect reduces annual building energy consumption and temperature-related mortality. The problem of UHI during hot season or in hot climate lies in its magnitude, which has been steadily increasing in recent decades. This increase is largely attributed to two main factors: global warming and urbanization.

As urban areas continue to grow and global temperatures rise, the challenge of mitigating UHIs becomes more pressing. Therefore, the aim is not to eliminate UHI but rather to reduce its magnitude to an acceptable level. Achieving this goal can be challenging. In general, one of the significant factors in mitigating the effects of urban heat islands is paying attention to the principles of urban design in urban construction and infrastructure. Fig. 3 summarizes possible strategies to mitigate UHI and the way they work. In Houston, Texas. It has been proven that reducing the impacts of UHI may save 82 million dollars and result in a 730 MW peak power reduction, which would result in an annual reduction of 170,000 tons of carbon emissions [3].

These strategies can be categorized based on the climatic emplacement. For example, [10] summarized the most appropriate mitigation strategies for each climate after analyzing urbanization rates, UHI intensity, etc. in Latin American cities.

Numerous studies have delved into the effects of various UHI mitigation strategies on air temperature regulation and energy consumption. A comprehensive review was conducted, encompassing 41 studies that spanned diverse Köppen climate classifications that 33 of them are about air temperature and 8 of them are about energy consumption. These studies predominantly relied on ENVI-met software, a widely utilized tool for simulating urban microclimates. The findings synthesized from these investigations shed light on the efficacy of various UHI mitigation approaches across different climatic contexts, providing valuable insights for urban planners and policymakers striving to create sustainable and comfortable urban environments. Detailed results of these studies are summarized in Table 1, offering an understanding of the nuanced relationship between mitigation strategies and their impacts on air

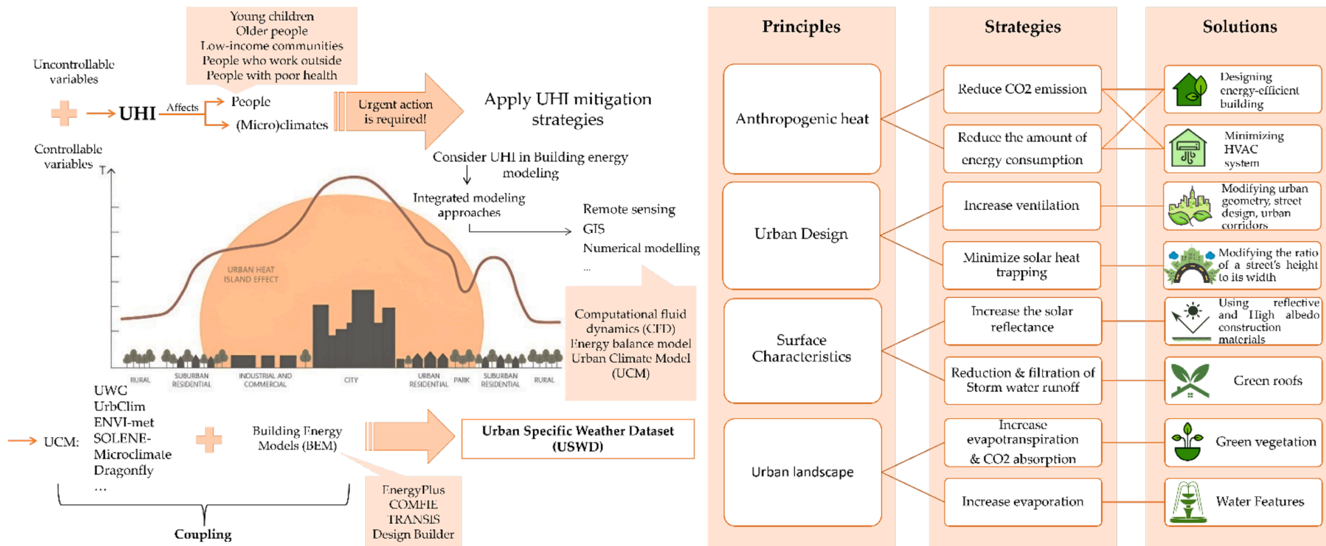

Fig. 1. The graphical abstract of the current review.

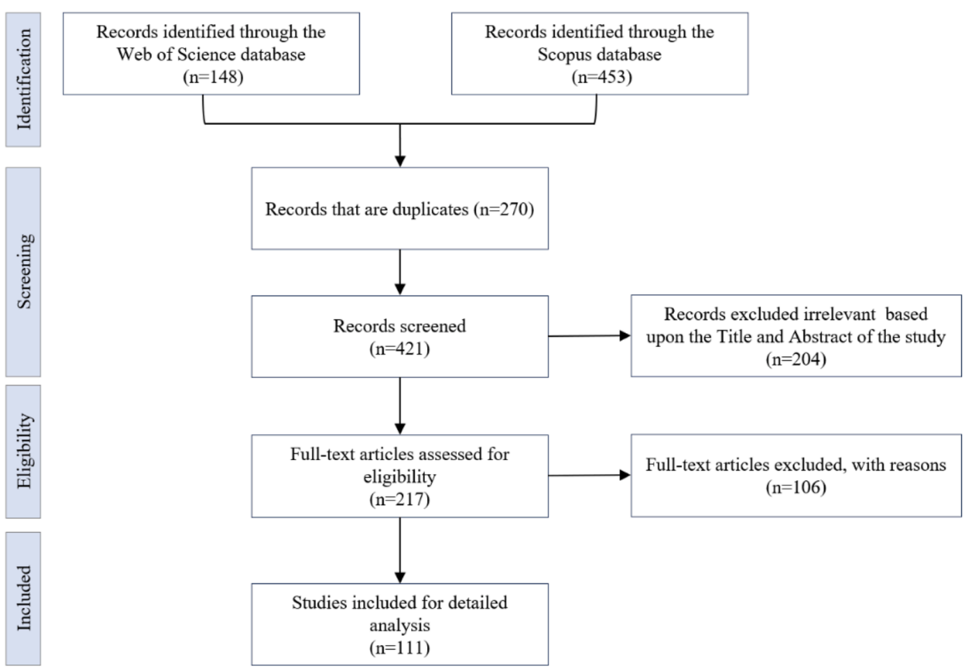

Fig. 2. The PRISMA flow diagram.

temperature dynamics and energy utilization within urban areas. Based on research and article reviews, increasing greenery has the greatest impact on reducing urban heat islands. By incorporating this into urban design and construction regulations, a significant improvement in the comfort of urban heat conditions can be observed (Table 2).

3. Factors causing UHI and impact of UHI

3.1. Exploring factors driving uhi

UHI is caused by the increased absorption and storage of solar energy by artificial surfaces compared to natural vegetation [52]. The significant contributors to UHI are the substantial amounts of heat generated by urban structures, diverting solar energy from its intended use and re-radiation, along with anthropogenic heat sources [53].

Various factors influence the intensity of UHI. As an uncontrollable variable, strong penetrative winds play a crucial role in dissipating heat accumulated in densely urbanized areas, thereby diminishing the severity of UHI. Wind flow emerges as a pivotal element in passive or active ventilation systems, aiding in the reduction of the cooling load of buildings and the UHI effect [54]. Similarly, clouds contribute to UHI mitigation by absorbing and reflecting both long and short-wave solar radiation, leading to a reduction in solar insolation. Wind speed, in conjunction with cloud cover, stands out as the most influential meteorological element affecting UHI formation [55].

Controllable variables like urban morphology and urban materials are among the fundamental drivers that result in UHI [56]. The Sky View Factor (SVF), as effective element on urban morphology, plays a significant role in UHI dynamics. Low SVF, found in densely built areas with narrow streets, helps mitigate UHI by providing shade and reducing solar radiation, keeping daytime temperatures lower. High SVF, typical of open spaces, allows for better nighttime heat dissipation, cooling

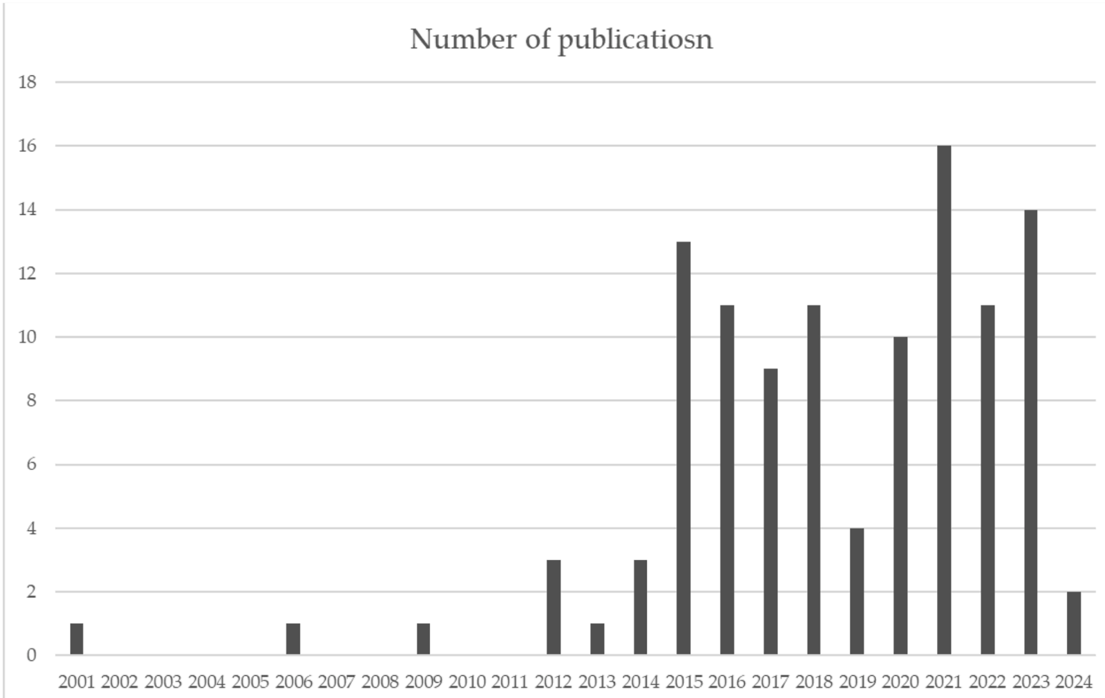

Fig. 3. Temporal distribution of the studies.

urban areas more effectively. However, moderate SVF can worsen UHI by allowing significant daytime heating while insufficiently dissipating heat at night, trapping warmth in urban areas [57]. Urban materials with low albedo alter an urban surface's energy balance by absorbing incoming solar energy, raising surface temperatures and overall ambient temperature [42,51,56]. UHI intensities can be categorized into two broad groups based on underlying factors:

1. Spatial factors encompass the impacts of changes in the spatial aspects of the urban environment, such as alterations in urban form and land cover patterns, on UHI intensity.
2. Temporal factors delve into how UHI intensities vary across different temporal scales, including yearly, seasonal, diurnal, and nocturnal fluctuations [58]. In Figs. 4 and 5, various factors causing and aggravating UHI are shown.

3.2. UHI impact analysis

The consequences of the additional warmth in cities have diverse practical implications, and whether they are deemed positive or negative depends on the macroclimate of the city [67].

Studies indicate that for every 1 °C temperature increase, the energy demand during summertime may rise by 2–4% [79]. Moreover, in the United States of America (USA), every 0.6 °C increase in air temperature raises power consumption for cooling by 1.5–2.0% [53]. Given that UHI is more pronounced at night, it is emphasized that a "nighttime-cooling effect" should be the norm, rather than an exception, for any potential UHI mitigation strategy" [73]. UHI effects can be classified under two broad categories: people and (micro) climates. However, the two are not mutually exclusive. Figs. 6 and 7 show its different effects on people and microclimate.

4. Methods of UHI study

Typically, weather data inputs are normalized, lacking specificity or tailored adjustments for individual sites influenced by both natural surroundings and built structures. This lack of detail can introduce uncertainties into simulations due to variations in local weather data and on-site material properties. Numerous studies have highlighted the substantial influence of urban microclimates on the accuracy of building energy performance calculations [81,82]. Generally, there are two ways to study UHI:

1. Observational approaches:
   - Field measurement
   - Satellite data -Thermal remote sensing
   - Small-scale modeling
2. Simulation approach (Numerical modeling):
   - Computational fluid dynamics (CFD)
   - Energy balance model (simplified model)
   - Urban Climate Model (UCM)

The simulation method involves using computer models to simulate the urban environment and predict future climate. Limitations include the need for specialized software and expertise and the fact that models may not accurately reflect real-world conditions [3]. Urban climate modeling is now recognized as a valuable tool for assessing the effectiveness of urban design measures aimed at enhancing the climate resilience of cities [83]. There are two main types of urban climate models (UCMs):

1. Parametric models: The Urban Weather Generator (UWG), Canopy Interface Model (CIM), UrbClim, CitySim.
2. Explicit models: ENVI-met, SOLENE-Microclimate, SOLWEIG, Dragonfly.

Both types of models have their characteristics and are used for different purposes. Parametric models are simpler and faster to run, but they may not provide as much detail as explicit models. Explicit models, on the other hand, are more complex and computationally intensive, but they can provide more detailed information about the microclimate [84].

Table 1
A summary of studies on the impacts of mitigation strategies on air temperature.

Location	Koppen climate classification	Mitigation principles	Software	Impacts
Putrajaya, Malaysia [11]	Af, Tropical rainforest climate	Tree canopy density and quantity High albedo pavements	ENVI-met HTB2	Simulations predicted an average air temperature reduction of 2.7 °C when compared with the current condition (cooling load reduction of up to 29%)
Athens, Greece [12]	Csa, Mediterranean/ dry-summer subtropical climate	Green roofs	Literature review and analysis of various studies	Reduce the average ambient temperature between 0.3 and 3 °C.
Oregon, USA [13]	Csb, Warm & temperate climate	High albedo surfaces (white material with albedo above 0.9)	ENVI-met	Simulations of courtyards with vegetation and a water pond showed 1.6 °C and 1.1 °C air temperature reduction. Increased the globe and mean radiant temperature (0.9 °C and 2.9 °C) and produced a cooler air temperature (1.3 °C) in comparison with a dark pavement.
Padua, Italy [14]	Cfa, Mild and moderate climate	Green ground Cool pavements Cool roofs	RAYMAN & ENVI-met	Decrease between 1 and 2 °C in UHI maximum intensity in all the points
Toronto, Canada [15]	Dfb, Continental climate	Urban geometry and density Cool pavement Cool roof Combined UHI mitigation techniques	ENVI-met	The maximum ground surface temperature was reduced by 7.9 °C in the detached area, 7.6 °C in the middle-rise area, and 7.9 °C in the high-rise area. The median roof surface temperature in the mid-day in a summer day decreased by 9.6 °C in the high-rise area and of 11.3 °C in the detached area.
Catania, Italy [16]	Csa, Mediterranean climate	Green roof Cool roof	Energy Plus	The sensible heat fluxes released by the roof to the outdoor environment are cut down in each city when using both green roofs (from 42% to 75%, depending on the climate) and cool roofs (about 75% when $r = 0.65$, and even more when $r = 0.80$).
Miami, USA [17]	Cfa, Tropical monsoon climate	Cool roof	DesignBuilder coupling with EnergyPlus	The maximum TRHG (through roof heat gain) flux was 54% lower for the PCM roof than the cool roof at a wide range of albedo. Similarly, the maximum sensible heat flux for the PCM roof type 40% lower than the cool roof technology for varying albedo.
Terni, Italy [18]	Csa, Warm temperate Mediterranean climate	High albedo materials	WRF Model	The increase of the albedo leads to a decrease of the urban temperature by up to 2.5 °C at daytime and also at nighttime.
Adelaide, Australia [19]	Csa, Mediterranean climate	Green roof (Covering 30% of the total roof area with green roofs)	ENVI-met	Reduce surface temperature by 0.06 °C.
Baghdad, Iraq [20]	BWh, Desert climate	Modifying height-to-width ratio	Envi-met	Higher exposure of the surfaces to solar radiation leads to increases in the amount of reflected and diffused solar radiation as well as the emitted thermal, which in turn increases the Tmrt.
Texas, USA [21]	Cfa, Humid subtropical with a hot summer climate	Cool pavement (modified asphalt concrete)	-	The modified HMA with 4.8% graphite reduces the pavement surface maximum temperature by 1.5 °C.
Sri Lanka [22]	Af, Tropical rainforest climate	Urban green infrastructure	ENVI-met	The results show that trees in the margin, green roofs, green walls, and combinations of all the above options reduce the temperature by 1.87 °C, 1.79 °C, and 1.86 °C.
Melbourne, Australia [23]	Cfb, Temperate oceanic climate	Green roof Cool roof	WRFv3.8.1 model WRF-UCM model	Maximum roof surface UHI is reduced during the day by 1 °C to 3.8 °C by increasing green roof fractions from 30% to 90%. By 2.2 °C to 5.2 °C by increasing the albedo of cool roofs from 0.50 to 0.85. Green roofs improve human thermal comfort by reducing the Universal Thermal Comfort Index by up to 1.5 °C and 5.7 °C for pedestrian and roof surface levels, respectively, and by 2.4 °C and 8 °C for cool roofs for the same levels.
Houston, Phoenix, Memphis, El Paso, Chicago, Boise USA [24]	Cfa, Hot & humid BWh, hot desert climate Cfa, humid subtropical BWh, hot desert climate Dfa, humid continental BSk, semi-arid continental climate	Roof vegetation, Trees, Grass coverage ratio	Urban Weather Generator (UWG) Rhinoceros 3D modeling tool: Grasshopper	The increase in grass coverage ratio was effective in hot climates in Houston and Phoenix but only slightly effective in Memphis, increasing the UHI effect in the other climate zones. The tree coverage ratio was an effective strategy for mitigating UHIs in most of the test case climate zones, especially in Houston and Memphis.
Belgrade, Serbia [25]	Cfa, Humid subtropical climate	Green roof	ENVI-met	Green roofs in Belgrade reduce pedestrian temperatures to 1.80 °C and roof level temperatures to 1.45 °C.
Guangzhou, China [26]	Cfa, humid subtropical climate	Permeable pavements (sintered ceramic porous brick (CB) and open-graded pervious concrete (PC))	Mathematics Calculation	Sprinkling could reduce the surface temperature of PPS by up to 10 °C, and lower the ratio of sensible heat flux to the net shortwave radiation of PIP and PCP to 13.12% and 29.62%, respectively, compared to their dry conditions. Compared to non-sprinkling conditions, the maximum air temperature above PIP and PCP could be decreased by up to 1 °C at a height of 0.3–0.9 m. The

(continued on next page)

Table 1 (*continued*)

Location	Koppen climate classification	Mitigation principles	Software	Impacts
				black globe temperature at the height of 0.5 m was reduced by up to 3 °C, compared to their dry conditions.
AL AIN, UAE [27]	BWh, Desert climate	Trees	WUDAPT ENVI-met	Despite the dense and high-speed construction, extensive use of trees improves climatic conditions and reduces the effects of urban heat islands.
Shiraz, Iran [28]	BSk, Cold semi-arid climate	Green walls	ENVI-met	Panel living wall systems can reduce the ambient air temperature by up to 8.7 °C. Additionally, the living wall reduces the temperature fluctuations by decreasing the maximum and increasing the minimum temperatures of the ambient air. During the hours of solar radiation, the temperature dropped by an average of 2.59 °C.
Niğde, Turkey [29]	Csb, Warm & temperate climate	green and impervious surfaces	Satellite images Statistical and geographical analyses ArcMap	The LSTs of the impervious surfaces are 5–10 °C higher than that of the green surfaces.
Lebanon, Beirut [30]	Csa, Mediterranean/ dry-summer subtropical climate	Green surfaces High albedo materials of the facades and roofs	ENVI-met	Reduction of ambient temperature reaching a maximum of 5 °C. The results showed the important role of green areas on the improvement of pedestrian comfort during daytime.
India, Nagpur [31]	Aw, Tropical wet and dry climate	Water bodies Vegetation cover	Landsat image Climate Consultant 5.3	The observed LST (°C) increased over urban built-up areas from 38.8 (°C) in April 2000 to 39.9 in April 2015, followed by water bodies, 28.47 °C to 29.6 °C, respectively. Whereas, the LST (°C) has been decreased over bare ground (42.2 °C to 40 °C), followed by sparse vegetation (40.99 °C to 39.5 °C) and vegetation cover (38.9 °C to 36.4 °C) from April 2000 to 2015.
Camden, New Jersey, USA [32]	Cfa, Warm and temperate climate	Shade of Trees	using logging thermistors, Microsoft Excel	Reduce air temperatures during hot days with a maximum temperature above 30 °C.
8 arid & semi-arid gulf region cities [33]	BWh, Tropical and Subtropical Desert Climate	Green spaces	ArcMap 10.7	The temperature difference between the bare areas and the urban areas ranges between 1 and 2 °C, between the bare areas and green areas ranges between 2 and 7 °C, and between the urban areas and green areas ranges between 1 and 6 °C.
Porto Alegre, Brazil [34]	Cfa, Warm, temperate, humid subtropical climate	Green roofs	Coupled simulations using ENVI-met and EnergyPlus	For the summer season, the reduction of the maximum operative temperature is 4.3 °C, whereas for the site without trees, the reduction was 2.8 °C.
Baghdad, Iraq [35]	BWh, Hot desert climates	Green spaces Cool pavement	ENVI-met	Using a cool pavement strategy led to a slight increase in thermal discomfort. The shade from trees or buildings or both led to a decrease in the PMV value by 2e4. Using surfaces that had a higher albedo factor led to increased values of Tmrt inside the urban canyon.
Seoul, South Korea [36]	Dwa, a humid continental climate with a dry winter	Pervious pavement	Mathematics Calculation	The difference between the surface temperature of wet and dry PCs was up to approximately 4 °C. PC contained 10% in weight amorphous metallic fiber, reduced the ambient heat by 20% when heated during the day and decreased it by 31% when cooling at night.
Greater Sydney, Australia [37]	Cfa, humid subtropical	Local ventilation	-	The local ventilation created by the sea breeze can help alleviate urban heat islands in the open low-rise gridiron and compact high-rise gridiron precincts with every 0.1 increase in relative wind velocity ratio leading to a 0.09–0.12 °C reduction in UHI intensity.
Mandaue, Philippines [38]	Af, Tropical rainforest climate	Increasing vegetation Adding open spaces Green roofs	ENVI-met	The addition of more urban spaces and trees could decrease air temperature by 0.2 °C on average. Green roofs could decrease air temperature by an average range of 0.2 °C–0.4 °C. A combination of trees, grasses and green roofs is used, and air temperature could be decreased by an average range of 0.1 °C–0.3 °C. When a combination of vegetation and green roof is employed, surface temperature could be decreased by an average range of 0.4 °C–1.1 °C.
Berlin, Germany [39]	Cfb, Oceanic climate	Cool roof Green roof	Coupling WRF with UCM	The daytime reduction of LST averaged over Berlin is 3.10 and 2.76 K for cool and green roofs, respectively.
Henan, China [40]	Dwa, humid subtropical	Water Bodies	Envi-met	Building density and man-made underlying surface are negatively correlated with temperature, humidity, and Physiological Equivalent Temperature value while greening rate and water body rate are positively correlated with microclimate. Overall, water bodies can improve outdoor comfort in summer and thus should be protected and developed in rural planning and design.
Hamad, Bahrain [41]	Cfa, Humid subtropical climate	Cool roof Green roof	DesignBuilder ENVI-met	In the microclimate simulation, average roof surface temperatures were 31.5 °C (cool) and 31.3 °C (green) versus 40.2 °C (conventional).

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Table 1 (*continued*)

Location	Koppen climate classification	Mitigation principles	Software	Impacts
Padua, Italy [42]	Cfa, Mild and moderate climate	Cool Pavements	ENVI-met Grasshopper tool: Ladybug	Reductions in atmospheric temperature: at the pedestrian level of 0.6 to 1.2 °Cat 15 m elevation, 0.2–0.4 °C.
Nicosia, Cyprus [43]	BSh, Hot semi-arid climate	Different building types & heights vegetated types	ENVI-met PVGIS system	The reduction of the built area by about 10% resulted in an air temperature reduction of 1.5 °C during the summer solstice. The soil temperature difference between the vegetated area, water, and pavement surfaces during summer solstice was above 24 °C.

4.1. Parametric models

Parametric models assume that the climate characteristics are constant in the urban canopy layer (UCL) in terms of the urban shapes, surfaces, materials, and vegetation.

4.1.1. Urban weather generator (UWG)

The Urban Weather Generator (UWG) is a simulation tool developed at MIT that estimates hourly values of air temperature and relative humidity in the Urban Canopy Layer (UCL) using meteorological data obtained at an operational rural weather station,[83–85]. It does this by coupling an atmospheric model with a BEM. The advantage of using UWG is that it first estimates the hourly urban canopy air temperature and relative humidity and then generates a morphed weather file in .epw format that captures the UHI effect and is compatible with many tools for building energy simulation. This model has been used widely in urban-scale digital and computational design workflows [70,84,86–88]. The UWG has four coupled modules [84]:

1. The rural station model (the forcing temperature): calculates sensible heat fluxes at the weather station.
2. The vertical diffusion model calculates vertical profiles of air temperature above the rural site.
3. The urban boundary layer model calculates air temperatures above the urban canopy layer.
4. The urban canopy and BEM calculate urban sensible heat fluxes and urban canyon air temperature and humidity (Fig. 8).

4.1.2. Urban boundary layer climate model (UrbClim)

The Urban boundary layer Climate model (UrbClim) is an urban climate model designed to simulate and study the UHI effect and other urban climate variables (wind speed, humidity, etc.) at a very high spatial resolution (of a few hundred meters) [90,91]. The model describes large-scale weather conditions down to the agglomeration level and calculates the effect of urbanization on the most critical weather parameters. UrbClim uses a land surface scheme with simplified urban physics combined with a 3D atmosphere boundary layer module. In UrbClim, the land surface scheme takes part of its inputs (wind speeds, temperatures and specific humidity near the surface) from atmospheric boundary layer model values (a basic 3D lower atmosphere model extending to a few kilometers). The simulations are validated using station data and satellite land surface temperature observations (UHI) [80,89].

4.1.3. Canopy interface model (CIM)

Canopy Interface Model (CIM) is a mesoscale atmospheric model that simulates the interactions between the atmosphere and the land surface, including vegetation. CIM is designed to function as a mesoscale and a microscale atmospheric model, as well as to provide better resolution for surface turbulence floxides in the city's urban canopy layer [92]. CIM calculates wind speed values along the vertical axis and air temperature values along the horizontal axis by applying differential equations for momentum and potential temperature [93].

4.1.4. CitySim

CitySim, a large-scale dynamic building energy simulation tool, was developed at the Swiss Federal Institute of Technology Lausanne (EPFL). The tool includes an important aspect in the field of many buildings' simulation: the building interactions (shadowing, light inter-reflections and infrared exchanges) [94]. CitySim is a comprehensive software tool that enables the simulation of urban energy flows, including UHI effects. It integrates building energy models, climate data, and urban morphology to evaluate the energy performance and thermal behavior of cities. In Fig. 9, inputs, outputs, advantages, and limitations of these tools are summarized.

4.2. Explicit models

Explicit models use an explicit 3D shape of the area of interest and mesh the urban surfaces and surrounding air volumes, providing a detailed representation of the microclimatic variables around the buildings.

4.2.1. ENVI-met

ENVI-met, a 3D microclimate simulation software, utilizes computational fluid dynamics and thermodynamics to model urban environments. It operates with a typical resolution of 0.5–5 m spatially and 1–10 s temporally, serving diverse applications like urban planning, building design, and energy efficiency, considering various climate factors. Designed to simulate surface-vegetation-air interactions, ENVI-met replicates day and nighttime temperatures, humidity, wind speed, and solar radiation in cities and evaluates the impacts of different building materials on surrounding climates. It facilitates assessing heat transfer between indoor and outdoor microclimates [43,93–96] and validates proposed urban heat island mitigation strategies by detailed microclimate simulation [43].

ENVI-met accurately simulates the process of transpiration, where plants release water vapor through their leaves. This process cools the leaves and subsequently the surrounding air, contributing significantly to the reduction of ambient temperatures [97].

The model is capable of simulating [95]:

- Flow around and between buildings;
- Exchange processes of heat and vapor at urban surfaces;
- Turbulence;
- Exchanges of energy and mass between vegetation and its surroundings;
- Particle dispersion and simple chemical reactions.

It's extensively used by urban planners, architects, and engineers to assess thermal comfort, air quality, and energy performance in urban areas, validated across various cities and microclimate conditions [93, 96].

4.2.2. SOLENE-Microclimate

SOLENE-Microclimat is employed to simulate Urban Heat Island (UHI) phenomena. This involves modeling the microclimate conditions

Table 2
A summary of studies on the impacts of mitigation strategies on energy consumption.

Location	Koppen climate classification	Mitigation principles	Software	Impacts
France [44]	Cfb, Warm, temperate, humid climate	Shadows of surrounding buildings	SOLENE-microclimate	13.5% lower evaluation of the daily energy consumption for building cooling
Abu Dhabi, UAE [45]	BWh, hot desert climate	vertical greenery systems (VGS)	SLUCM	A 5–8% decrease in cooling load and a significant reduction in urban air temperature by approximately 0.7 to 0.9 °C, reducing the UHI intensity by almost half.
Montreal, Canada [46]	Dfb, Cold and temperate climate	Cool roofs	Elements	Decreases the predicted cooling and total energy demand of the building with TMY. The deviation between such prediction and the mean energy demand as evaluated with AMY weather data is also increased.
Cairo, Egypt [47]	BWh, hot desert climate	Buildings Orientation	EnergyPlus	An air-conditioned building with a southern facade is found to consume less energy, whereas a western facade results in 26% higher annual energy consumption compared to the southern facade.
Nanjing, China [48]	Cfa, humid subtropical climate	Urban geometry	ENVI-met, HTB2, Virvil plugin	The buildings located in NE-SW streets that hold the lowest Ta consume the minimum cooling energy, whereas the cooling demands of the buildings in E-W and N–S streets are almost identical and the maximum.
Tehran, Iran [49]	BSk, Cold semi-arid climates	High albedo material and vegetation	ENVI-met	Decreases the cooling load by 29%.
Kirkuk city, Iraq [50]	BSh, hot semi-arid climate	Buildings form and orientation	Green Building Studio & BIM	The findings reveal that the T-shaped model achieved the lowest energy consumption when oriented at a 285° angle, offering valuable guidance for designing and constructing energy-efficient buildings in Kirkuk.
Erbil, Iraq [51]	Csa, hot-summer Mediterranean climate	Double-skin façade	EnergyPlus & ClimateStudio	Using a double-skin facade in Erbil can reduce annual cooling demand by 9% to 14% and save up to 116,574 kWh of energy per year.

within urban areas to understand how various factors, such as building materials, vegetation, and urban layout, contribute to increased temperatures compared to surrounding rural areas. SOLENE-Microclimat is developed by the CRENAU, Nantes, France [98]. SOLENE-Microclimat is the result of the coupling of SOLENE (a thermo-radiative model), a thermal building model, and Code-Saturne (a CFD open-source code developed by French Electricity Company - EDF) [97,99,100].

4.2.3. *Solar and Longwave environmental irradiance geometry (SOLWEIG)*

Solar and Longwave Environmental Irradiance Geometry (SOLWEIG) is a microclimate model that is used for modeling outdoor thermal comfort and UHI effects. SOLWEIG is a radiation model that can make climate estimations (such as sunshine durations, shadow patterns and daily shading) and analyze the complex interaction between urban design and the thermal environment. It is also capable of simulating spatial variations of 3D radiation fluxes and Mean Radiant Temperature (MRT) in complex urban settings. It was developed by the Urban Climate Group of the Department of Earth Sciences, University of Gothenburg, Sweden [94,98].

4.2.4. *Dragonfly*

Dragonfly - a Grasshopper plugin - is a software tool that models the urban heat island effect by simulating the radiation balance of urban areas. It is capable of predicting the temperature distribution of urban surfaces, including buildings, roads, and parks, under different weather conditions and land use scenarios. Dragonfly takes into account various factors such as solar radiation, longwave radiation, and thermal properties of different surfaces to model the urban heat island effect. Dragonfly uses the Urban Weather Generator (UWG) simulation engine to morph EPW files to account for the UHI effect. The resulting urban EPW files can be used to assess the impact of UHI on building energy use and outdoor thermal comfort [101]. In Fig. 10, inputs, outputs, advantages, and limitations of these tools are summarized.

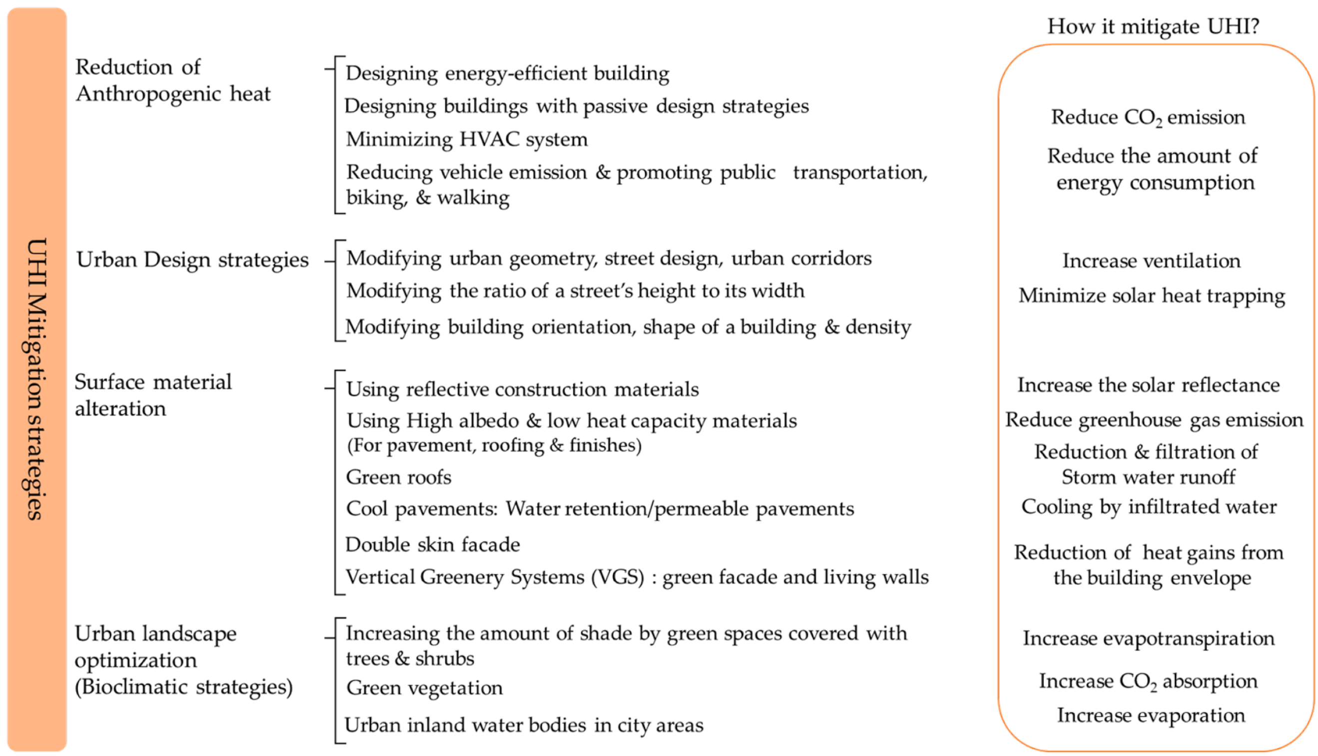


Fig. 4. UHI mitigation strategies and mechanism [3,4,11–25,27–31,33,35,38,39,41–44,46,59–66].

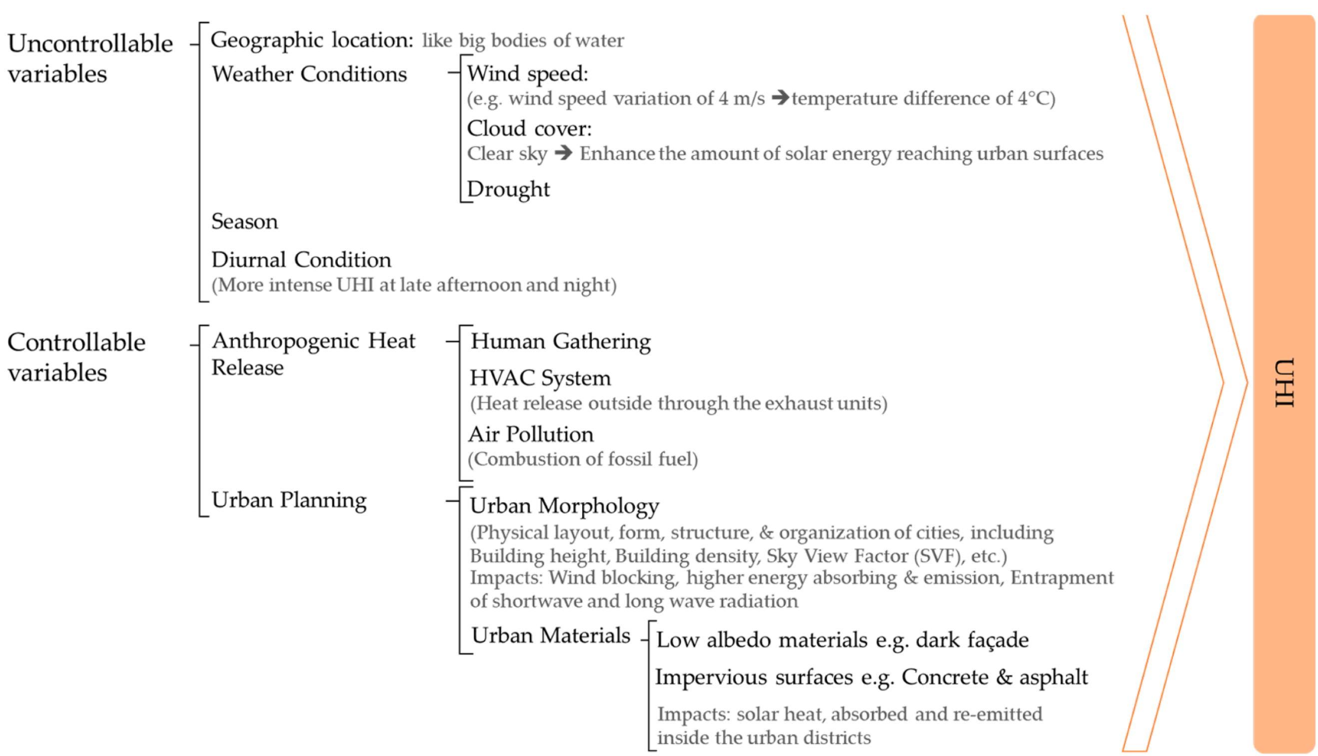


Fig. 5. Causes of UHI [3,4,15,23,42,43,51,53–56,58–61,66–78].

4.3. Comparing methods of UHI study

In previous chapter, 8 methods of UHI study are explained. Now with comparing their output and scale, it would be easier to choose the most proper method to gain more accurate energy consumption output.

It can be inferred from the table that models like ENVI-met and CitySim, which cover a broad range of parameters, can provide detailed insights into both microclimate and building energy performance. However, the absence of certain parameters in some models, such as wind direction in UWG, highlights potential limitations that could affect

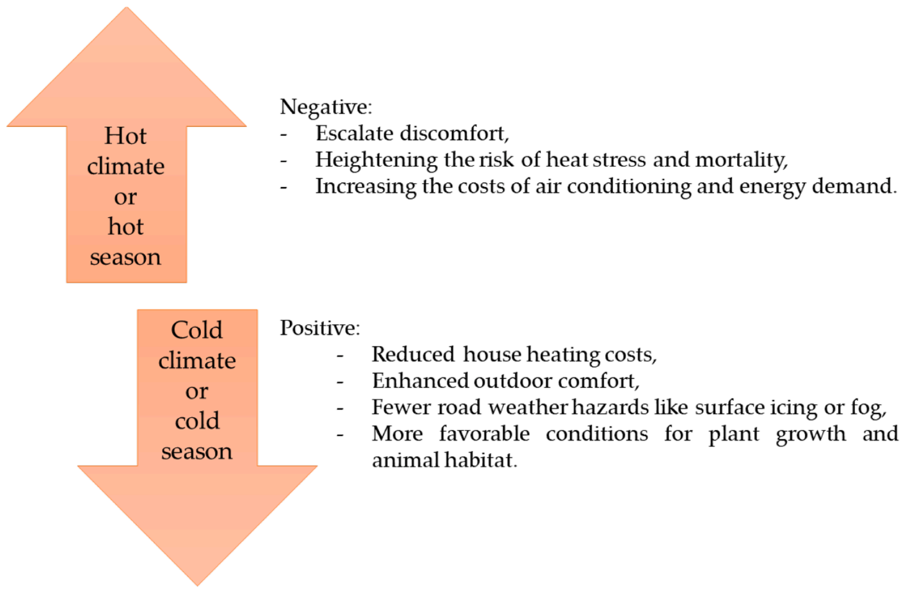


Fig. 6. Diverse UHI effect depending on the macroclimate [67].

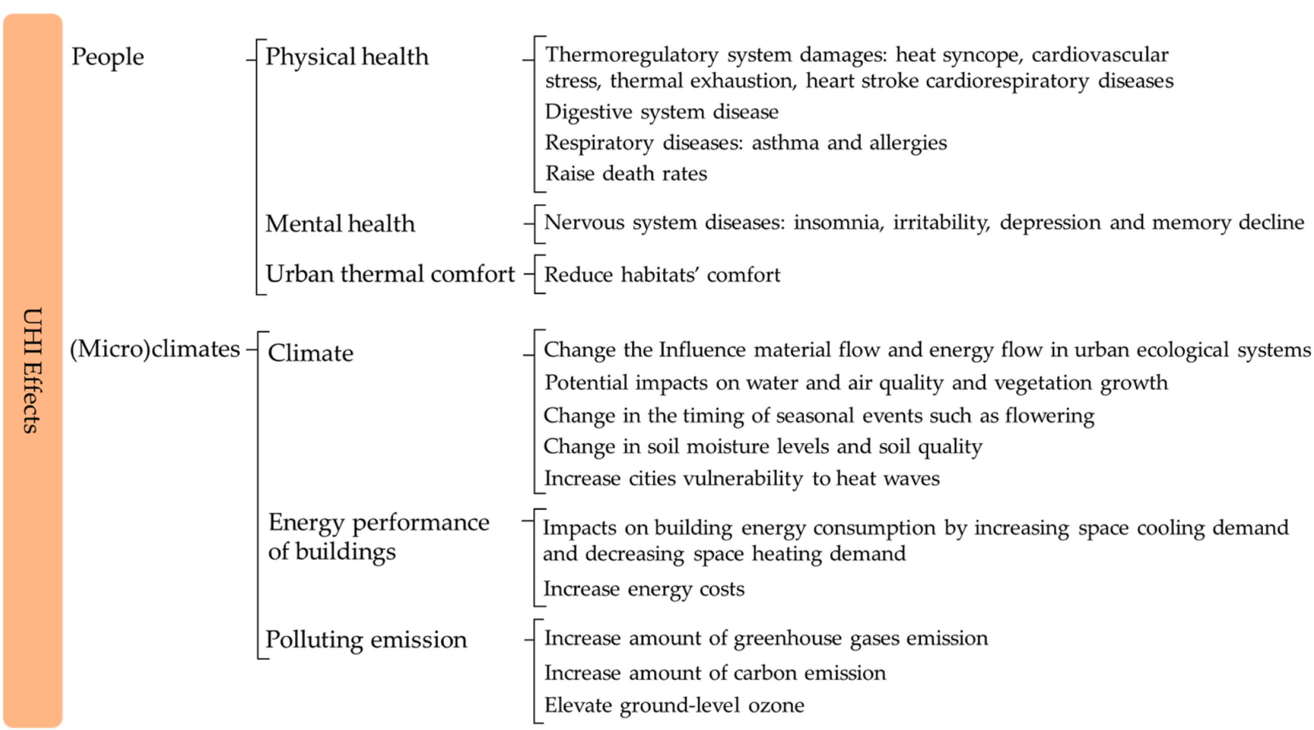


Fig. 7. Classification of urban heat island effects [1,3,4,14,42,43,53,55,59–62,66,67,68,70,73,74,76,80–82].

the accuracy of simulations.

The choice of the best UCM model depends on the specific research question and spatial scale of interest. For example, ENVI-met would be suitable for analyzing the microclimate around a single building and would emerge as the leading tool for microscale studies (Figs. 11 and 12).

There are four different methods to take into account the urban microclimate and UHI in building design simulations:

1. Stand-alone building simulations using weather datasets:
   This method involves using weather datasets that include air temperature and relative humidity, wind velocity and direction, and solar to assess the exchange of heat and moisture between indoor and outdoor environments.
2. Coupling building BEM with UCM:
   This method involves coupling BEM with UCM to account for the local microclimate and the effect of neighboring buildings when conducting energy simulations.
3. Hybrid modeling approaches:
   This method involves using hybrid modeling approaches between the building scale and the city scale to account for the interaction between both scales.
4. Street models:
   This method involves modeling the street scale, which defines a

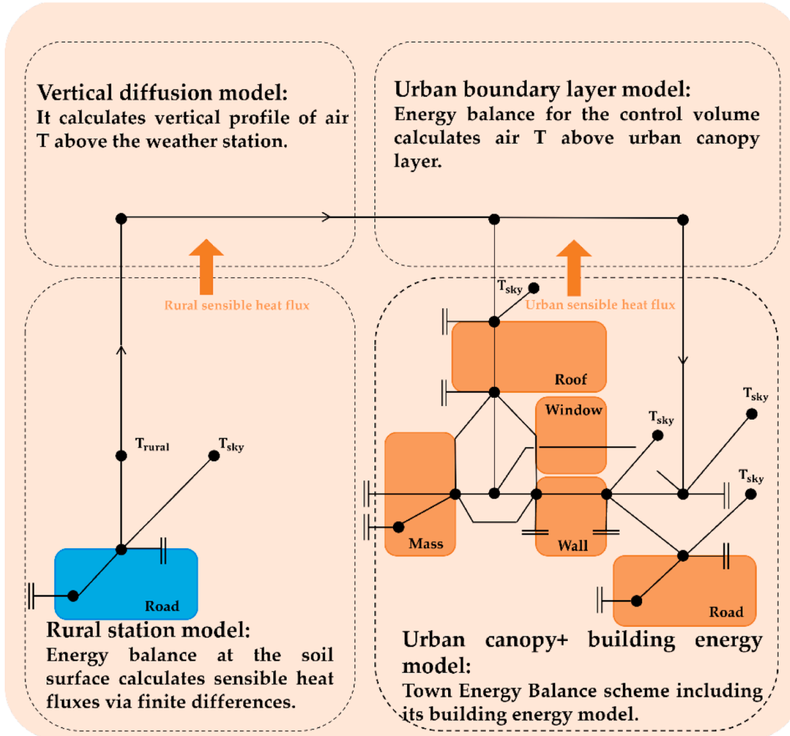


Fig. 8. UWG coupled modules [89].

Parametric models

	Inputs	Outputs	Advantages	Limitations
UWG	. Meteorological data . Urban morphology . Building geometry . Surface materials . Albedo . Anthropogenic heat . Windows SHGC . land use	. Morphed weather file [epw]: contains the urban microclimate in terms of the local hourly temperature (°C) and humidity (%).	. An alternative to computationally expensive simulations . Ability to simulate the microclimate at a high spatial resolution . Flexible and can be adapted to different urban contexts and climates	. Requiring detailed input data . Time-consuming . Without an explicit 3D geometry of the zone examined, the UWG cannot simulate radiations.
CIM	. Meteorological data . Weather data . Urban morphology . Land cover data . Building geometry . Vegetation parameters (leaf area index, canopy height, etc.) . Soil properties (soil moisture content, soil texture, etc.)	. Meteorological variables . Urban-scale weather data that accounts for the UHI effect . Carbon dioxide exchange . Sensible heat flux . Latent heat flux	. Ability to capture the complex interactions between the atmosphere and vegetation . Ability to simulate turbulent kinetic energy (TKE) . Useful for studying the effects of land use changes on the atmosphere	. Requires detailed information on vegetation parameters . Complex model that requires significant computational resources . Requiring a certain level of expertise in numerical modeling
UrbClim	. Meteorological data . Urban morphology . Land use data . Land cover data . Building information . Anthropogenic heat flux . Vegetation index	. Morphed weather file [epw] . UHI maps . Maps and visualizations of Climate parameters . Fine-scale temperature differences . Air quality	. Being faster than high-resolution mesoscale climate models by at least two orders of magnitude . Accuracy despite simplicity . Ability evaluate the effects of different urban design strategies on the microclimate	. High computational requirements . Complexity . Requiring a significant amount of input data
CitySim	. Meteorological data . Weather data . Building geometry . Materials . Occupancy patterns . Lighting and equipment schedules	. Air temperature & humidity . Mean Radiant Temperature . Energy consumption . Indoor temperature & air quality . Indoor comfort levels . CO2 emission . Daylight availability	. User-friendly interface . Ability to evaluate the effectiveness of different urban design strategies in mitigating the UHI effect . Giving reasonable results despite the simplifications	. High computational requirements . Significant amount of input data . Reliance on simplified equations

* Meteorological data (air temperature, wind speed, humidity, solar radiation, cloud cover)
* Climate parameters (Outdoor air temperature & humidity, wind speed and direction, and surface temperatures)
* Urban morphology (building heights, street layouts, & land cover types)

Fig. 9. Characterisation and classification of UHI parametric models.

Explicit models

	Inputs	Outputs	Advantages	Limitations
ENVI-met	. Meteorological data . Weather conditions . Urban morphology . Land use data . Vegetation cover . Properties of urban surfaces	. Morphed weather file [epw] . Climate parameters . Air quality . Outdoor comfort indexes (PMV, PET) . A rough estimation for the energy performance of a building	. User-friendly interface . Ability evaluate the effects of different urban design strategies on the microclimate . The surface-plant-air interactions model . Generating new weather data . consideration of all aspects of vegetation cooling including transpiration rates.	. Not working with air temperature values below 0°C. Complexity . Time-consuming . The need for extensive data input . May not always accurately capture the effects of local topography or microclimates
SOLENE-Microclimate	. Meteorological data . Urban geometry . Surface properties . Atmospheric conditions . Land use data . Building characteristics	. Climate parameters . Comfort indexes (MRT, PET, UTCI) . Indoor comfort conditions or building energy demands	. Reduced Computational cost . A building thermal model was developed . Ability to represent the entire urban environment	. Lack of accuracy . Limited spatial resolution . Data requirements . Computational complexity . Lack of validation . Cannot be used for simulations longer than a few days
SOLWEIG	. Meteorological data . Urban geometry & geographical information (latitude, longitude and elevation) . Shortwave radiation . Surface albedo & emissivity	. Climate parameters . Mean radiant temperature (MRT) . Outdoor Thermal Comfort indexes (PET) . Surface temperature maps . Radiation balance maps	. Ability to evaluate the effectiveness of different urban design strategies in mitigating the UHI effect . User-friendly interface	. Requiring detailed input data . May not accurately simulate complex urban geometries or highly variable surface properties
Dragonfly	. Meteorological data . Weather data . Building geometry . Land cover data	. Morphed weather file [epw] . Pollutant concentrations . Wind speed distributions . Heating & cooling load . Surface temperature maps . Thermal comfort indices	. Ability to evaluate the effectiveness of different urban design strategies in mitigating the UHI effect . Identifying most vulnerable areas to heat stress in a city	. Requiring high-resolution meteorological data . Requiring a certain level of expertise in Grasshopper and energy modeling

* Meteorological data (air temperature, wind speed, humidity, solar radiation, cloud cover)
* Climate parameters (Outdoor air temperature & humidity, wind speed and direction, and surface temperatures)
* Urban morphology (building heights, street layouts, & land cover types)

Fig. 10. Characterisation and classification of UHI explicit models.

Climate parameters	Model:	Parametric models				Explicit models			
	Software	UWG	CIM	UrbClim	CitySim	ENVI-met	SOLENE-Microclimate	SOLWEIG	Dragonfly
Air temperature		✓	✓	✓	✓	✓	✓	✓	✓
Surface temperature		✓	✓	✓	✓	✓	✓	✓	✓
Air humidity		✓	✓	✓	✓	✓	✓	✓	✓
Solar radiation		✓	—	✓	✓	✓	✓	✓	✓
Wind speed		—	✓	✓	✓	✓	✓	✓	✓
Wind direction		—	✓	—	✓	✓	✓	—	✓
Cloud coverage		—	✓	—	✓	✓	—	—	✓

Fig. 11. Output climate parameters of parametric and explicit models.

confined air volume bordered by walls, where the effects of solar trapping and airflow patterns can be readily defined.

Overall, these methods aim to improve the prediction of building energy performance by accounting for the local microclimate and the effect of neighboring buildings [84].

5. Coupling BEM with UCM

Coupling in building simulations refers to the integration of models from different software to enhance the reliability of simulation results [2]. This process involves combining building energy models with urban canopy models, computational fluid dynamics (CFD) or thermo-radiative simulation tools to study interactions between the

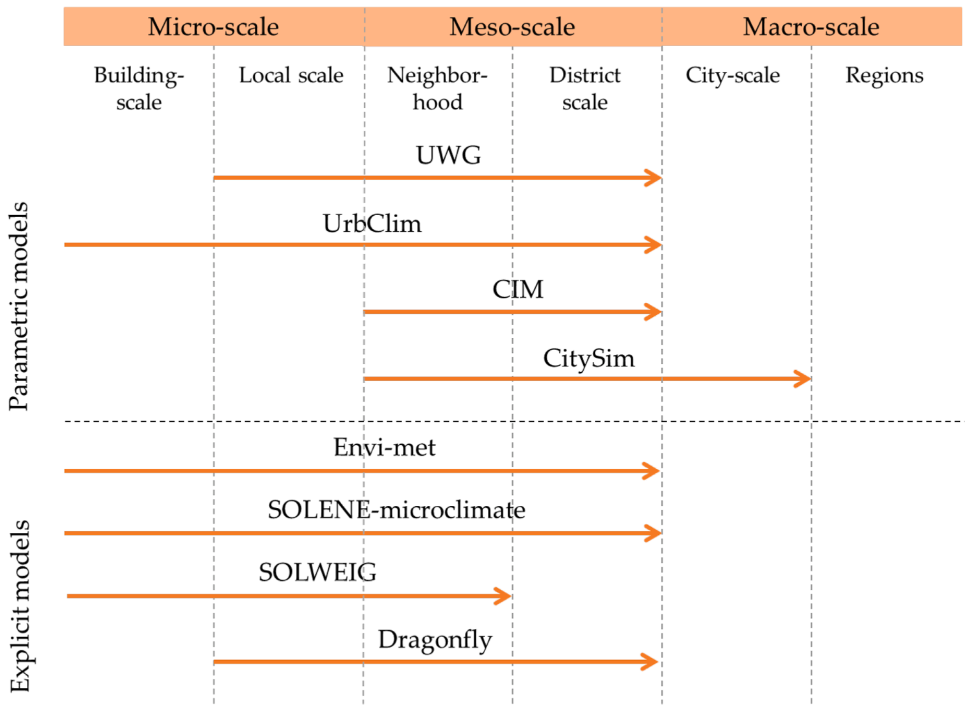


Fig. 12. Spatial scale of parametric and explicit models.

outdoor environment and a building's energy performance [34].

The coupling can be achieved through various methods, such as full dynamic coupling, quasi-dynamic coupling, or intermediate coupling, each offering different levels of computational cost and accuracy. The choice of coupling method can significantly affect results, especially in non-insulated building cases and during periods of high discomfort risk, such as summer. The coupling method employed has a notable effect on factors like indoor temperature and heating demand. However, the detailed impact of coupling is subject to variations based on factors such as heating power and insulation. Overall, coupling plays a crucial role in understanding the complex dynamics between microclimate and building energy consumption. Still, careful consideration of the method employed is essential to ensure accurate and reliable results [102].

Using coupling brings benefits to simulation like allowing feedback of buildings' use on the local climate and reciprocal [100]. A coupled method can be used to increase the accuracy of input data, differentiating the cooling and heating needs in larger spaces. Coupled simulations are also used to test future climate change scenarios [26,101]. There are different levels of coupling BEM with UCM, including strong coupling, weak coupling, and chaining. Typically, weak coupling or chaining is the preferred approach, with strong coupling being less common. In both strong and weak coupling methods, there is interaction between UCM and BEM simulations. Finally, the chaining method involves conducting a complete UCM simulation and then incorporating the outcomes into weather files utilized by a BEM tool [95,99]. Fig. 13 introduces coupling and chaining methods.

A review of 11 articles was conducted. The investigation encompassed climate classification, analyzed area, method and software, climate parameters, and resultant outputs to gain deeper insights into the coupling and chaining methods. Ultimately, the study unveiled the discernible impacts of considering microclimatic factors and UHI effects on building energy demands and how UHI impacts on building energy consumption by increasing space cooling demand and decreasing space heating demand. Table 3 shows the results of the review. The table effectively captures the diversity of methodologies, software tools, and climatic conditions under which these studies were conducted,

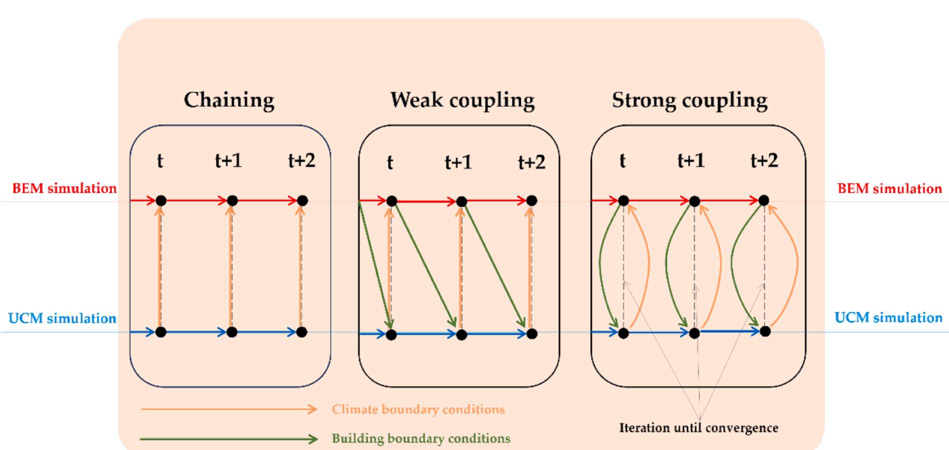


Fig. 13. Sketch to introduce coupling and chaining methods [84].

Table 3
A summary of studies on coupling and chaining methods.

Location	Koppen climate classification	UHII detected	Software & method	Impacts	Output	Parameter						Analyzing area
						Temperature		Relative Humidity	Solar radiation	wind		
						Air	Surface			Speed	Direction	
Wuhan, China [77]	Cfa, Humid subtropical climate	0.45 °C (yearly average)	Coupling ENVI-met & COMFIE	The heating load is 3.5 % larger, the cooling load is 3.9 % smaller, and the total energy load is smaller by 0.2% compared to the reference simulation.	USWD	✓	■	■	■	■	■	High-rise building (1 office building & 3 residential buildings)
Manama, Bahrain [103]	BWh, Hot arid climate	2.2 °C	Chaining ENVI-met with IES-VE, Meteonorm	The IES-VE predicted total electricity consumption during summer was 595 MWh, deviating by 6% from the actual measured consumption (560 MWh). The weather station energy simulation predicted the energy demand to be 664 MWh, with a 15% deviation against actual consumption.	USWD	✓	■	✓	■	■	■	University
Thessaloniki, Greece [104]	Cfa, Mild and moderate climate	-	Coupling ENVI-met & EnergyPlus	The higher T_{air} values in the urban districts captured in the USWDs resulted in a rise in the annual cooling energy needs of between 13.4% and 28.2%, depending on the study area.	USWD	✓	■	✓	✓	✓	■	4 different urban districts Residential
Manchester, UK [105]	Cfb, Humid temperate oceanic climate	8 °C	Coupling ENVI-Met & IES-VE	The summer UHI alone increased the air conditioning load between 9% and 12%.	-	✓	■	✓	■	✓	■	3 residential & commercial buildings
Guangzhou, China Frankfurt, Germany [95]	Cfa, Humid subtropical climate Cfb, Temperate-oceanic climate	1.2 °C	Coupling ENVI-met & EnergyPlus	A considerable increase of 1.1% in the cooling load was observed after taking into account the actual thermoradiative environment. A remarkable increase of 9.4% on the cooling load was observed after considering the impact of infiltration of the local hotter and more humid atmosphere.	Hourly sensible & latent cooling loads, Hourly heating load	✓	✓	✓	✓	✓		A 150 $m \times$ 150 m district with a row layout of buildings. Target building: The building in the center of the district
Lusail, Qatar [87]	BWh, Hot desert climate	-	Chaining UWG with EnergyPlus	Increased cool-down charges between 5.1 and 15.6%.	-	✓	■	✓	■	■	■	Residential tower
Rome and Barcelona [106]	Csa, Mediterranean Climate	2.6 °C in February & 1.9 °C in August	Chaining UWG with Design Builder (EnergyPlus)	Results confirm the relevance of urban morphology to the UHI intensity. Warmer temperatures lead to an average increase in energy demand from 10% to 35%, according to different urban densities.	-	✓	■	■	✓	■	■	Ciampino airport (Rome)
La Rochelle, France [63]	Cfb, Warm and temperate	-	Coupling SOLENE-microclimate & EnviBatE	Wind velocity decreases up to 80%, and the effect on an existing nearby building solar irradiation is reduced by 7%.	-	✓	■	■	■	✓	✓	District
Lyon, France [98]	Cfa, Humid subtropical climate	-	Coupling SOLENE-microclimate & BuildSysPro	UHI can decrease indoor air temperatures by an average of 0.15 °C. This decrease is mainly due to complex compensations between	-	✓	■	■	✓	■	■	An isolated cubic building & the same building located in a theoretical urban environment.

(continued on next page)

Table 3 (*continued*)

Location	Koppen climate classification	UHII detected	Software & method	Impacts	Output	Parameter						Analyzing area
						Temperature		Relative Humidity	Solar radiation	wind		
						Air	Surface			Speed	Direction	
				short and long-wave radiative heat transfers as well as aeronautics. The combined effect of UHI and other environmental factors can modify indoor air temperatures by up to 1.3 °C.								
Lausanne, Switzerland [93]	Dfb, Warm, humid continental climate	-	Coupling the canopy interface model (CIM) & CitySim	9.65% average increase in heating demand for the entire campus.	-	✓	✓	■	✓	✓	✓	EPFL University & its campus
Duran, Ecuador [107]	Aw, Hot and humid climate	0.86 °C to 1.59 °C (during the wet season) 0.52 °C to 1.42 °C (during the dry season)	Coupling UWG & TRNSIS	An increase in the cooling energy needs of buildings ranging from 12 to 70 %.	-	✓	■	✓	■	■	■	City of Duran

highlighting the impacts of different coupling strategies on building energy performance and UHI effects.

By presenting a comparative analysis of various studies conducted across different regions and climates, the table offers valuable insights into how coupling and chaining methods can enhance the accuracy of UHI simulations. The table illustrates how these methods account for localized microclimatic conditions, resulting in more precise predictions of energy demand and thermal comfort within urban environments. While Table 3 provides a comprehensive overview of existing studies, it also highlights several critical challenges and limitations inherent in the use of coupling and chaining methods.

One of the primary issues is the variability in the effectiveness of these methods across different climatic regions and urban contexts. For instance, the table shows that the impact of coupling methods on energy demand and UHI intensity can vary significantly, depending on factors such as urban morphology and local climate. This variability underscores the need for careful consideration when selecting and applying these methods, as their effectiveness is not universally consistent.

Moreover, the table points to the computational complexity and resource demands associated with coupling and chaining methods, particularly when integrating detailed microclimatic data with building energy models. This complexity can limit the practical applicability of these methods, especially in large-scale urban studies or in regions where high-quality input data is not readily available. Additionally, the table does not fully address the potential trade-offs between accuracy and computational efficiency, which is a crucial consideration for urban planners and researchers working with limited resources.

Another critical observation is that while the table effectively summarizes past studies, it does not provide a clear pathway for overcoming the challenges identified. The discussion could be enriched by proposing strategies for optimizing coupling and chaining methods, such as the development of more efficient algorithms or the use of hybrid approaches that balance detail with computational feasibility. Furthermore, the table could benefit from a more explicit discussion on the limitations of current methodologies and the potential for future research to address these gaps, particularly in terms of improving the integration of UHI models with broader urban planning tools and frameworks.

The effectiveness of these methods may depend on various factors, such as the specific context and objectives of the simulation study. Therefore, it is essential to carefully evaluate and compare different methods based on their accuracy, efficiency, and applicability to the specific research or practical context.

Indeed, the coupling method presents a spectrum of challenges and advantages, a selection of which are delineated below:

Coupling ENVI-met with COMFIE integrates thermal zone definition in COMFIE and the height resolution in ENVI-met, yielding enhanced precision in weather data and improved accuracy in simulation outcomes, particularly for high-rise buildings [77].

In coupling ENVI-met and EnergyPlus, ENVI-met air temperature and relative humidity outputs are too detailed to be directly used in EnergyPlus, thus necessitating the derivation of an averaged value [84]. However, currently, EnergyPlus and ENVI-met are considered the most reliable tools for integrating building thermal performance (EnergyPlus) with outdoor microclimate simulations (ENVI-met). Both tools are well-regarded in academic and professional circles and have been thoroughly validated through field measurements across various climates [34].

The coupling of CitySim and CIM is characterized by its one-directional interaction, where reciprocal data flow is absent. CIM does not incorporate the thermal loads arising from system operations. Consequently, this coupled approach is better tailored for estimating energy consumption at the district level rather than for the environmental design of individual buildings.

6. Discussion and research limitations

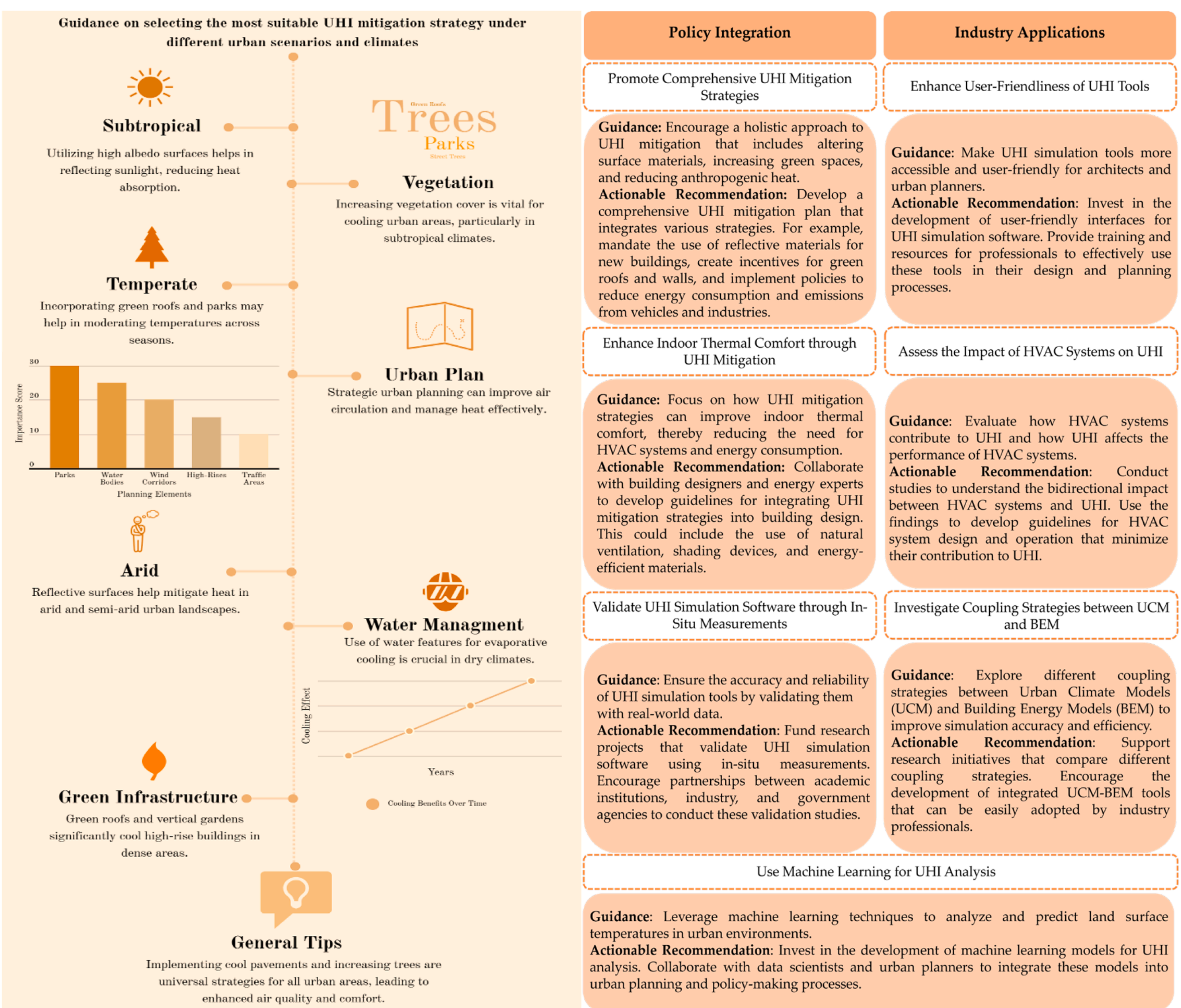
The effectiveness of UHI mitigation strategies is influenced by various factors, including the specific context and objectives of the simulation study. Therefore, it is essential to carefully evaluate and compare different methods based on their accuracy, efficiency, and applicability to the specific research or practical context. The long-term impacts of climate change on UHI, including the effects of rising temperatures and extreme weather events, need to be studied to understand the efficacy of current UHI mitigation strategies. Utilizing machine learning for UHI Analysis and predicting Land Surface Temperature (LST) in different climates can provide valuable insights for urban planners and policymakers. By following the guidance points presenting in (Fig. 14-a), policymakers and industry stakeholders can effectively integrate UHI mitigation strategies into their planning and development processes, leading to more sustainable and resilient urban environments.

Based on these findings, several recommendations for policy integration and industry applications can be made: promote comprehensive UHI mitigation strategies, enhance indoor thermal comfort through UHI mitigation, validate UHI simulation software through in-situ measurements, enhance user-friendliness of UHI tools, assess the impact of HVAC systems on UHI, investigate coupling strategies between UCM and BEM, and use machine learning for UHI analysis (Fig. 14-b). By following these recommendations, policymakers and industry stakeholders can effectively integrate UHI mitigation strategies into their planning and development processes, leading to more sustainable and resilient urban environments.

Several limitations were identified in the reviewed literature:

Temporal Scope: The reviewed literature primarily focuses on studies from the past decade, offering valuable insights into recent trends but potentially neglecting historical perspectives and long-term trends in UHI dynamics. Including studies from earlier periods could provide a more nuanced understanding of UHI evolution and improve predictive modeling capabilities.

Diversity of Simulation Software: The review covers eight commonly used UHI simulation software packages, potentially overlooking insights from lesser-known solutions. Future research should broaden the range of software analyzed to provide a more comprehensive evaluation of UHI simulation capabilities, including exploring the strengths and limitations of each.



(a)   (b)

Fig. 14. (a) The most suitable UHI mitigation strategies tailored to different conditions, (b) specific guidance for policy integration and industry applications.

One limitation of this review is the exclusion of the Weather Research and Forecasting (WRF) model. While WRF is a powerful tool for urban heat island (UHI) studies, it operates at a larger spatial scale compared to the other software reviewed. This review focuses on models that are more suitable for detailed, localized UHI analysis, which may limit the applicability of the findings to broader regional or global contexts.

Local Development Control Regulations: The article may not fully address how local development control regulations impact urban heat island formation and the effectiveness of mitigation strategies. Future studies should consider the role of regulatory frameworks in shaping UHI outcomes.

Scale of UHI Phenomena: UHI phenomena occur at various scales, necessitating models that capture both macro-level trends and micro-level details. Understanding seasonal and diurnal variations in UHI intensity across different seasons and throughout the day remains a significant challenge.

Integration with Other Domains: Integrating UHI models with other domains (such as air quality, hydrology, and energy) necessitates understanding intricate interactions and developing coupled models that account for feedback loops. This integration is essential for a holistic approach to urban planning and sustainability.

Climate-Specific Bibliometric Analysis: While the current study's scope precluded comprehensive statistical analysis of software trends and climate-strategy correlations, we propose a follow-up study integrating bibliometric analysis to systematically evaluate these relationships across Köppen climate zones and seasonal variations.

By addressing these limitations, future research can enhance the overall quality and depth of UHI studies, providing more comprehensive and applicable insights for urban planners and policymakers.

7. Conclusions

The reviewed literature has predominantly focused on either the phenomenon of UHI or the specific domain of UHI simulation tools. This article seeks to fill a critical gap by offering a comprehensive synthesis of relevant insights pertaining to the causes of UHI, its multifaceted impacts, and the diverse array of strategies available for its mitigation, drawing from an extensive review of scholarly works. Furthermore, this article endeavors to provide an exhaustive exploration of eight prominent UHI simulation software tools. The input and output data of the software, its advantages and limitations are explained. Furthermore, coupling BEM with UCM is discussed. Coupling allows for a more comprehensive understanding of the energy performance of buildings in the context of the surrounding urban environment. By furnishing such detailed analyses, this article aims to equip architects and urban designers with the necessary knowledge to select the most suitable software for their specific temporal and spatial considerations, thereby facilitating informed decision-making in the pursuit of UHI mitigation strategies. The following areas are suggested for future research:

- The most studied strategies for reducing UHI include altering surface materials and increasing green spaces. There is a need to investigate other factors, such as reducing anthropogenic heat.
- Investigating the impact of UHI mitigation strategies on indoor thermal comfort.
- Validating each software through in-situ measurements.
- Enhancing the user-friendliness of UHI tools for architects and urban planners.
- Assessing the impact of HVAC systems on UHI and vice versa.
- Investigating the impact of different coupling strategies between UCM and BEM on the accuracy and efficiency of simulation.
- Investigating how climate change will affect the efficacy of current UHI mitigation strategies. This could include studying the long-term impacts of rising temperatures and extreme weather events on urban heat islands.
- Using Machine Learning for Urban Heat Island Analysis and Predicting Land Surface Temperature (LST) in Urban Environments in different climate.
- Analyzing future bibliometric to examine software-climate strategy linkages across Köppen zones and seasonal variations.

CRediT authorship contribution statement

Elham Bahadori: Writing – original draft. **Fatemeh Rezaei:** Writing – review & editing. **Bao-Jie He:** Writing – review & editing. **Milad Heiranipour:** Writing – review & editing. **Shady Attia:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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