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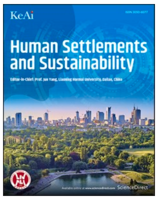

Review article

An expert-based ↱review of Mean Radiant Temperature across ten research domains at urban and building scales[☆]

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ABSTRACT

Mean Radiant Temperature (MRT) has emerged as a critical parameter for evaluating human thermal comfort in built environments and microclimates across the globe. Defined as the uniform temperature of an imaginary enclosure where the radiant heat exchange with the human body matches that of the actual, non-uniform environment, MRT offers a comprehensive representation of radiative thermal exposure. Understanding MRT requires examining its relationship with human thermal indices, long-term fluctuations in outdoor settings, and impacts on human health and climate change patterns. This is a relevant topic for urban and landscape planners, architects, urban designers and health professionals, with accurate MRT assessment recognized as key to developing thermally comfortable spaces. Precise MRT measurement benefits occupants through improved thermal comfort conditions and energy efficiency. Furthermore, implementing MRT-informed design strategies helps reduce cooling demands, making it more affordable to maintain comfortable indoor and outdoor environments. This 'ten domains contribution' provides an overview of MRT's importance in human thermal comfort assessment, measurement and modelling techniques, relationships with indoor and outdoor environmental characteristics, implications for health studies and exposure during extreme heat events and heat waves, optimization strategies for buildings and HVAC systems (Heating, Ventilation, and Air Conditioning Systems), and future perspectives in the context of global to local climate change.

1. Introduction

As the frequency and intensity of heat waves rise under global climate change, cities face increasingly complex challenges in maintaining thermal livability. Urban microclimates are shaped not only by air temperature but also by the combined effects of surface materials, solar exposure, urban form, vegetation, and anthropogenic heat. In this context, Mean Radiant Temperature (MRT or Tmrt) has emerged as a key parameter in human-biometeorological research and climate-responsive design. Unlike air temperature alone, MRT quantifies the total radiative heat load from the surrounding environment, accounting for both longwave and shortwave radiation fluxes and therefore plays a

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central role in determining outdoor thermal comfort [1,2].

Traditionally, MRT has been applied in empirical models and urban design tools to estimate thermal comfort in open spaces, often using simplified proxies like globe thermometers or radiative simulation models such as SOLWEIG (SOlar and LongWave Environmental Irradiance Geometry) or RayMan. With the advent of physics-informed machine learning, remote sensing, and real-time sensor networks, MRT is rapidly evolving from a static research metric to an operational parameter for climate adaptation [3].

Recent studies underscore the need for MRT to be reconceptualized in light of emerging climate realities. For instance, Lau et al. [4] demonstrated that MRT is more sensitive than air temperature to the geometric layout of cities, particularly during heat waves. Antoniou et al. [5], using high-resolution microclimate modeling throughout the built environment, found that MRT values in Mediterranean cities may reach up to 65°C under fixed urban geometry when applying future meteorological boundary conditions derived from climate model outputs, dramatically increasing pedestrian heat stress. These findings illustrate a growing knowledge and application gap: while MRT is theoretically robust and physiologically meaningful, it is often underutilized in large-scale urban assessments due to measurement complexity, lack of standardized protocols, and limited integration into policy or real-time management tools.

First, measurement remains inherently indirect, as no sensor can capture MRT directly; instead, it must be derived from multiple radiative and environmental variables, introducing cumulative uncertainties and calibration challenges. For example, globe thermometers require equilibrium times ranging from 4 to 20 min depending on diameter, introducing temporal uncertainty in dynamic environments. Second, existing monitoring technologies face practical barriers such as high cost, installation complexity, and limited accuracy, particularly under dynamic outdoor conditions, which restrict their deployment in long-term or large-scale studies. Accurate six-directional radiative measurements may require up to 12 sensors in a net-radiometer configuration, while indoor studies report simultaneous MRT differences exceeding 10°C within the same space. Third, the lack of standardized measurement protocols and interoperable datasets hinders comparability between studies and limits integration into operational urban planning and building control systems. This paper addresses this gap by investigating ten key domains identified through keyword co-occurrence analysis, comprehensively capturing the interdisciplinary scope of MRT research in urban climate evaluation while maintaining analytical depth. The ‘expert-based review’ format follows a well-established approach for clarifying technical concepts, surfacing frontier challenges, and framing interdisciplinary dialogue in environmental science. Thus, each domain explores a core dimension of MRT theory, measurement, modeling, or application, emphasizing relevance to climate adaptation, public health, and urban resilience.

The aim is threefold. First, providing a comprehensive synthesis of MRT definitions, drivers, and measurement techniques. Second, exploring how multi-modal monitoring systems combining satellite data, drone-based thermal imaging, and low-cost sensor networks can enable widespread accessibility of MRT assessment at high spatial and temporal resolution. To understand how the thermal environment is assessed remotely, it is essential to explore how surface temperatures are measured and by which factors they are effected. At the satellite scale, Liang et al. [6] demonstrated that land-use change, particularly the rapid expansion of built-up land, was the dominant driver of vegetation dynamics between 2000 and 2020 in Tianjin, China, and exerted a stronger influence on NDVI than climate change. Furthermore, Wu et al. [7] found that a 147.3% increase in impervious surfaces over two decades in Yingtan, China, correlated strongly with rising land surface temperatures and intensified urban heat island effects. Moreover, the study of Karadeniz et al. [8] provided spatially explicit evidence showing that ecosystem-service hotspots identified through significant clustering can guide regional planning priorities and support targeted conservation and resource-management policies in Turkey. Finally, highlighting the emerging role of artificial intelligence (AI) and physics-informed neural networks (PINNs) in improving predictive accuracy, reducing dependence on intensive field data, and enabling dynamic control of thermal conditions. In this regard, the study of AlKhaled et al. [9], the researchers showed that the online developed WebMRT machine-learning tool can accurately predict summertime MRT with high performance ($R^2 = 0.92$ and RMSE = 3.4°C), offering a fast and accessible alternative to complex numerical models for urban heat-exposure assessment. Furthermore, Özbey et al. [10], found that an Artificial Neural Network (ANN) model using only four temperature inputs can predict indoor MRT with high accuracy ($R^2 = 0.94$), showing a fast and cost-effective alternative to complex calculations and expensive measurements.

A key contribution of this paper is the reframing of MRT as both a diagnostic and prognostic control variable for urban design and planning. While previous research treats MRT primarily as an outcome metric within thermal comfort ↱models, we position it as a design-constraining variable influencing zoning codes, façade ↱materiality, vegetation strategies, and heat-health alert systems.↱

Beyond modeling, the paper also emphasizes the coupling of MRT with nature-based solutions (NBS), urban energy systems, and digital health tools. Previous studies have indicated that MRT can vary by several to tens of degrees Celsius between sunlit and shaded conditions with NBS inclusion. MRT measurements obtained through monitoring campaigns or simulations can serve as a basis for evaluating the cooling effectiveness of green infrastructure, identifying thermal hotspots exacerbated by reflective materials or HVAC waste heat, and issuing real-time health alerts through smartphone applications. The studies by Ridha [11] and Xie et al. [12] showed that MRT can serve as a reliable parameter for assessing the effectiveness of urban interventions, provided that monitoring and modeling systems are robust, scalable, and context-sensitive.

In another research context, heat exposure and thermal comfort have been the subjects of limited studies investigating the role of MRT within low-income communities. As reported by Kajjoba et al. [13], while indoor thermal conditions in low-income housing in Kampala, Uganda, were generally within acceptable comfort ranges (MRT = 24.2–25.6 °C), particulate matter levels ($PM_{2.5}$ and PM_{10}) significantly exceeded WHO guidelines, highlighting indoor air quality (IAQ) as the main environmental health risk. To structure this paper, we address the following research questions:

1. What are the most effective methods for measuring and modeling MRT at different spatial scales?
2. How can emerging technologies [e.g., AI, Internet of Things (IoT), remote sensing] be leveraged to expand MRT monitoring?
3. What is the role of MRT in evaluating climate adaptation strategies, such as urban greening and passive design?
4. How can MRT data be integrated with health risk frameworks to protect vulnerable populations during heat waves?
5. What are the pathways for integrating MRT into the urban planning, regulatory tools, and resilience policies?

In answering these questions, we aim to reposition MRT as a central operational metric in climate-responsive urban design and policy. Rather than being confined to research settings, MRT should guide zoning codes, public space design, building regulations, and emergency planning. By bringing together state-of-the-art technologies, emerging applications, and open research questions, this paper provides a roadmap for advancing MRT from theory to practice in the service of thermally resilient, healthy, and equitable cities (Fig. 1).

2. Methodology

Based on a bibliometric analysis of the Scopus database spanning 30

Fig. 1. Cross-scale conceptual framework positioning MRT as a mediating variable between building energy systems, urban climate processes, and human thermal response.

years (1995–2025) using the crossed key terms 'Mean Radiant Temperature' and 'Built Environment', Fig. 2 shows that MRT research experienced exponential growth after 2018, with annual publications exceeding 230 by 2025. This surge reflects the increasing urgency to quantify radiant heat flux in warming urban environments and the proliferation of advanced simulation tools like ENVI-met and RayMan.

Geographically, research is dominated by the United States and China, with strong European contributions from the United Kingdom, Germany, and France (approximately 300 documents each). Significant research also originates from Japan, Canada, India, and Australia, demonstrating MRT's universal relevance across diverse climatic zones. Thematically, publications underscore MRT's multidisciplinary nature. Environmental science (17.5%) leads, focusing on urban cooling and landscape architecture, followed by medicine (15.5%), which links MRT to thermoregulation and heat-related mortality. Engineering (14.6%) addresses measurement and HVAC integration challenges, while earth and planetary sciences (9.4%) and social sciences (7.8%) explore climate modeling and thermal comfort's impact on public space use. Moreover, emerging contributions from energy (5.6%) and computer science (3.5%) indicate the growing application of AI and machine learning for predicting complex radiant environments.

There are ten domains that address mean radiant temperature and urban climate as well as indoor environmental conditions.

2.1. *Comparative focus: Mean Radiant Temperature as a microclimatic parameter rather than a thermal index*

Understanding how thermal environments influence human thermal comfort and physiological state has long been a central focus in human biometeorology. To address limitations in assessing thermal conditions and develop universally applicable methods, researchers have turned to human body heat balance calculations. Büttner's pioneering 1938 work represents an early attempt to model human thermal equilibrium [14, 15].

Despite the long history, most outdoor heat-exposure studies still treat radiation as a secondary modifier of air temperature-driven discomfort, which systematically underestimates stress during clear-sky heat waves and overestimates protection under breezy conditions. MRT is not a comfort index; it is a microclimatic state variable representing the net radiative environment experienced by the body.

Human heat balance modeling extends beyond pure physics, as it must account for active thermoregulatory responses that modify heat exchange processes. These physiological mechanisms play a critical role and require integration into any comprehensive thermal model. In outdoor environments particularly, radiative heat exchange constitutes a dominant component of the overall energy balance. Radiative heat flux quantifies the thermal energy transferred through radiation between the human body surface and surrounding surfaces. The corresponding

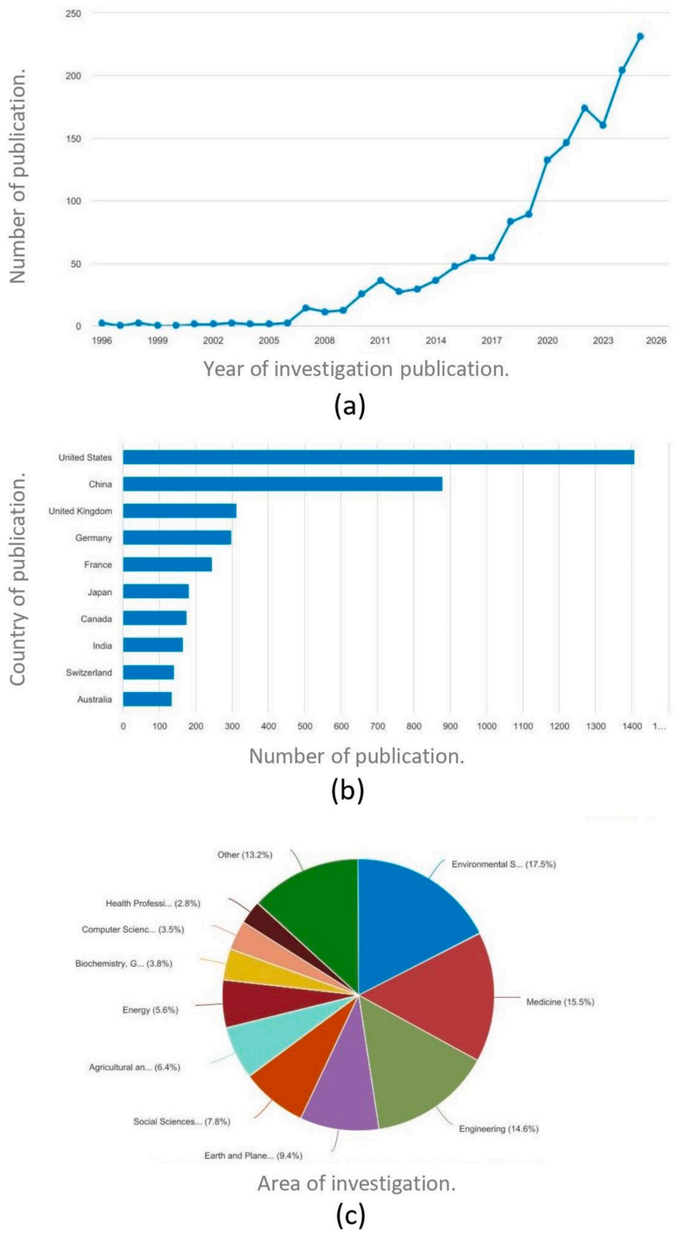

Fig. 2. Bibliometric overview regarding MRT research fields from Scopus: (a) temporal evolution of MRT research over 30 years; (b) number of publications by country; (c) distribution of MRT research across disciplinary fields.

equation is:

$$R = A_{DU} \cdot f_{cl} * f_{eff} \cdot \varepsilon_{\dot{}p}\, \sigma \times (Tmrt^{4} - T^{4}) \quad [14] \tag{1}$$

In Eq. (1), A_{DU} represents the unclothed body's surface area, while f_{cl} denotes the clothing area factor that accounts for surface expansion due to garments. The parameter f_{eff} quantifies the ratio of actual body surface to the effective radiating surface (standardized at 0.7 for standing persons). Additional variables include εp, the emissivity of human skin and clothing surfaces, σ, representing the Stefan-Boltzmann constant, T, represents the air temperature in (°C) and Tmrt (MRT), which characterizes the mean radiant temperature of the surrounding environment.

Furthermore, in outdoor environments, MRT is significantly affected by direct solar radiation. Accurately calculating the direct solar radiation absorbed by the human body requires consideration of the Projected Area Factor (f_P) [15–17]. The f_P is defined as the ratio of the direct solar radiation projected area (A_p) to the effective radiative area of the human body (A_{eff}), as expressed in Eq. (2):

$$f_p = A_p/A_{eff} = A_p/(A_{DU} \cdot f_{cl} \cdot f_{eff}) \quad [15–17] \tag{2}$$

Two important aspects should appear in the discussion about the calculation of thermal ↱indices and estimation of MRT.↱

1. ↱The amount of radiation fluxes indoors and outdoors
2. ↱The additive effect of MRT on Tair and its contribution to thermal indices.↱

MRT represents the temperature of a hypothetical uniform black enclosure (with unit emissivity, $\varepsilon = 1$) that would produce equivalent radiative heat gain on the person's body surface, considering its specific body orientation (azimuth angle) and posture as experienced in the actual heterogeneous thermal radiation field (Fundamentals, A.H., 2005 [18]).↱

MRT is an input parameter for many thermal indices and is strongly influenced by radiative processes, which shows the highest variability in magnitude. MRT has different temporal ↱characteristics, highest in the sun, near sunlit walls and close to air temperature in temperate indoor settings and ↱in the shade of trees and buildings (with less effect of directly exposed global radiation) [19]. Accordingly, MRT is a synthetic microclimatic parameter derived from multiple radiative components rather than measured directly.

2.2. Mean Radiant Temperature and outdoor environments

The investigation of MRT is context-dependent, varying significantly between different environments. Accordingly, this study examines MRT from outdoor to indoor settings, highlighting key differences between these domains.

2.2.1. Outdoor environmental drivers of long-term variations in Mean Radiant Temperature

The design and layout of the outdoor environment could have major implications for ↱microclimate and MRT variations. Urban microclimate ↱involves localized climate conditions within urban areas, which can differ substantially from ↱surrounding rural areas due to factors such as building density, street orientation, surface material and coating and ↱vegetation [20,21]. Various urban design and urban form ↱components could influence MRT fluctuations. Here, we elaborate on issues related to ↱several key components and factors associated with street network structure, street canyon ↱design, orientation of buildings and streets, and the structure of urban blocks. In addition, ↱issues related to material use and albedo are discussed given their importance.↱

Street networks and their structures play a crucial role in shaping the urban microclimate. The ↱connectivity and centrality of street networks determine the flow of air and the distribution ↱of heat within urban areas. For instance, gridded street networks, characterized by short ↱street segments and frequent intersections, could provide better capacities to adapt to ↱adverse events [22,23]. Such configurations enhance ↱connectivity, which facilitates air movement and reduces heat accumulation, thereby ↱improving thermal comfort. Conversely, dendritic street networks, which resemble the ↱structure of a tree, often lack appropriate levels of connectivity. This can lead to poor air ↱circulation and higher air temperatures in certain areas. However, dendritic street networks can be reconfigured through the strategic integration of pedestrian and cycling pathways that establish connectivity between cul-de-sac streets and the broader road network, thereby enhancing ventilation patterns and mitigating thermal stress [22,23]. ↱

While the structure of street networks is important, it should not be considered without ↱paying attention to the way street canyons are shaped. In other words, geometry-related ↱issues such as sky view factor, aspect ratio (height-to-width ratio), and street orientation ↱also matter. Street canyons, formed by buildings flanking both sides of a street, significantly impact urban microclimate and MRT. The aspect ratio of street canyons influences the amount of solar radiation received and the wind flow within the canyon. High aspect ratios (deep canyons) can reduce solar exposure and increase shading, which is beneficial for reducing temperatures during hot summer days [23]. However, deep canyons can also trap heat and restrict wind flow, leading to higher nocturnal temperatures and urban heat island effects [24]. Optimal design measures for street canyons could include orienting streets to maximize shading during the hottest hours of the day. For instance, in some contexts, East-West oriented streets can provide shading during midday, reducing solar heat gain and improving outdoor thermal comfort [25]. Additionally, integrating greenery and green infrastructure, such as trees and bioswales, into street canyons can further ameliorate microclimate by providing shade and facilitating evapotranspiration [26]. The direction of streets relative to prevailing wind patterns could also influence the distribution of heat and air flow. For example, streets oriented parallel to prevailing wind directions can enhance wind channeling effects, increasing air movement and reducing temperatures [27,28]. In hot-arid and temperate climates, aligning buildings along East-West streets can maximize south-facing facades, increasing winter solar heat gain while minimizing summer heat gain. This orientation can reduce cooling energy demand and improve indoor thermal comfort. However, the optimal orientation may vary depending on local climatic conditions and the geometry of the street canyon [24,29].

The design and layout of urban blocks also play a significant role in shaping the urban microclimate. Smaller blocks with higher intersection density can improve connectivity and air flow, reducing heat accumulation and enhancing thermal comfort [30]. Additionally, mixed-use development within urban blocks can increase street vibrancy and reduce car dependency, further contributing to a cooler urban environment by reducing heat exhaust. Integrating green and open spaces within urban blocks can provide additional cooling benefits. Trees and vegetation can reduce surface temperatures through shading and evapotranspiration, while open spaces can facilitate air movement and reduce heat stress [26]. Furthermore, regarding courtyards inside building blocks, once courtyards are sufficiently tall to become fully or nearly fully shaded ($W/H < 1$), the influence of courtyard height on MRT becomes minimal [31].

Apart from layout and design measures, the materials used in the outdoor environment and their albedo could also impact urban microclimate and MRT fluctuations. Albedo refers to the reflectivity of surfaces, determining how much solar radiation is absorbed or reflected. High-albedo materials reflect more solar radiation, reducing heat absorption and lowering surface temperatures, which can mitigate the urban heat island (UHI) effect and improve thermal comfort [30,32]. Conversely, low-albedo materials absorb more solar radiation, leading to higher surface temperatures and exacerbating the UHI effect, resulting in elevated temperatures and increased heat stress.

High-albedo materials, such as light-colored concrete, reflective coatings, and cool roofs, can lower MRT by reflecting solar radiation and reducing heat absorption [30,32]. While these materials contribute to lower daytime surface and air temperatures, their effect on MRT and outdoor thermal comfort remains limited [33]. Low-albedo materials, such as asphalt and dark-colored concrete, increase MRT by absorbing and re-emitting solar radiation, causing higher MRT values during the day and maintaining elevated temperatures at night. Combining high-albedo materials with other cooling strategies, such as urban vegetation and water features, can further amplify the benefits for urban microclimate and MRT [30,32].

In summary, the design and layout of the outdoor environment and the type of materials used in the built environment have profound implications for urban microclimate and MRT fluctuations. Optimal design measures include enhancing street network connectivity, optimizing street canyon aspect ratios, orienting buildings and streets to maximize shading and wind flow, designing urban blocks to improve air movement and integrate green spaces, and using high-albedo materials. These measures can collectively reduce heat stress, improve thermal comfort, and contribute to the resilience of urban areas against climate-related challenges [20,21,26].

2.2.2. *Interactions of Mean Radiant Temperature with thermal comfort and Urban Heat Island (UHI) effects*

The urban heat island (UHI) effect, which causes urban areas to be warmer than their rural surroundings, is intensified by high MRT, leading to greater health risks during extreme heat events. Recent multi-city studies confirm that elevated MRT not only raises daytime temperatures but also sustains nocturnal heat stress, a key contributor to mortality during heat waves. MRT exacerbates the Urban Pollution Island (UPI) phenomenon, where heat interacts with air pollution to elevate ozone and $PM_{2.5}$ levels, amplifying cardiovascular and respiratory risks [34]. This dual threat underscores the importance of integrated urban planning to safeguard public health [34]. Emerging models now integrate bioclimatic indicators, such as Universal Thermal Climate Index (UTCI) and Wet Bulb Globe Temperature (WBGT), to better capture the synergistic impact of MRT on physiological strain especially for vulnerable populations like the elderly and outdoor workers [35].

MRT is a dominant factor in human outdoor thermal comfort on clear and calm summer days, often outweighing air temperature alone; high MRT levels lead to increased thermal discomfort, reducing the usability of outdoor spaces and negatively impacting quality of life [36–39]. Recent field studies underscore the dominant role of surface materials, solar exposure, and sky view factor (SVF) in modulating MRT [38]. To mitigate thermal discomfort, integrating vegetation, water features, and cool materials into urban environments can substantially lower MRT and enhance thermal comfort. For instance, combining water bodies with trees in urban parks has been shown to provide the best regulation of microclimate and comfort compared to using either element alone [37,39]. Advanced urban simulations using ENVI-met and SOLWEIG now enable fine-grained assessments of MRT under different urban design scenarios. For example, integrating reflective pavements, shading canopies, and deciduous tree corridors has proven highly effective in lowering MRT by up to 12°C during peak hours [39].

MRT is a key driver of urban heat island (UHI) intensity, as it reflects the cumulative radiant heat present in urban areas. Urban densification, material choices, and anthropogenic heat emissions elevate MRT, leading to more pronounced UHI effects. He et al. [35] argue that the MRT-UHI linkage is non-linear and context-specific, requiring localized climate zoning and microclimate diagnostics. The interaction between heat waves and UHI can lead to localized amplifications of heat, with less urbanized districts sometimes being more sensitive to these synergies. While factors such as air moisture and wind can help alleviate some of the exacerbated heat, the overall trend is toward higher UHI intensity as MRT increases. Additionally, higher MRT and intensified UHI effects raise the demand for indoor cooling, resulting in greater energy consumption and further environmental impacts [38].

Furthermore poorly ventilated urban canyons can trap longwave radiation at night, delaying cooling cycles and reinforcing nighttime UHI. These effects are projected to worsen under climate change, with some urban cores experiencing a annual increase in MRT by 0.3–0.5°C per decade without mitigation (IPCC AR6 WGII, 2022). In addition, intensified MRT contributes to increased cooling energy demand, shifting the peak load toward early evenings and overburdening electricity grids. The resulting feedback loop increases energy consumption, leading to more waste heat further fuels UHI intensity.

2.2.3. *Universal methods and emerging instruments for estimating Mean Radiant Temperature across multiple scales*

Universal methods for MRT include numerical simulations (e.g., ray-tracing and CFD models) and in-situ measurements using globe thermometers and radiometers, while novel technologies such as infrared thermography, UAV-based sensing, and AI-assisted predictive modeling enhance precision and scalability across various spatial contexts (Fig. 3).

The globe thermometer, consisting of a black hollow sphere with a thermometer at the centre of it, has been the most widely used instrument to determine the MRT due to its simplicity, low financial cost and ease of development. The original 150 mm-diameter black matt copper sphere was introduced by Vernon in 1930s [40], with Humphreys developing the most commonly globe thermometer used, the 40 mm-diameter blackened table-tennis ball [41].

These have been extensively employed for indoor comfort studies and post-occupancy evaluation surveys, while the huge increase in outdoor comfort studies in the early 2000s followed the extensive use of globe thermometers outdoors. However, the long response time of the traditional 150 mm-diameter globe, which can be over 20 min long for the sensor to reach equilibrium, renders it unsuitable for outdoor environments, with the rapidly changing conditions.

A systematic comparison aiming to develop a globe thermometer for outdoor use, investigated the impact of different materials and their properties and thickness on the response time significantly reducing the response time by reducing the sphere's heat capacity [42]. The suitability of the spherical shape of the globe has been raised for outdoor studies i.e., where people are walking rather than sitting- with good correlation found in higher latitudes where the sun is lower in the sky but might lead to overestimations of MRT in lower latitudes [43].

As the black globe assumes people are dressed in black from head to toes, which may be overestimating the impact of solar radiation on the MRT, globes of flat grey color have been used in outdoor comfort campaigns [1,44], with a paint reflectance of 0.3 providing the most accurate results.

Correction factors have also been developed to account for the sensitivity of the globe to the wind [1], particularly important in open environments with different convection coefficients for different cities [20,43], with the need for these to be calibrated locally [21].

New advances in radiant cooling systems have highlighted the shortcomings of globe thermometers [45] and have led to the development of novel instruments and technologies for MRT measurements.

Such a devise includes the integration of non-contacting surface temperature sensors on the six faces of a cube, which can evaluate MRT along with radiant asymmetry [46]. The 'cube' has demonstrated to have an extremely short response time of 0.1 s, and it eliminates the convective errors, addressing the shortcomings with the globe thermometer and leading to more accurate MRT measurements.

For this reason, instrument selection must be framed as a decision problem governed by dominant error sources rather than convenience or tradition. Table 1 summarizes the principal MRT measurement approaches, their dominant biases, and appropriate use contexts.

2.2.4. *Advanced numerical tools for calculating Mean Radiant Temperature*

There exists a range of advanced simulation tools to model Mean Radiant Temperature (MRT) ↱in distinct areas, each with its own computational approach, input variables, and ↱assumptions regarding radiative exchange and human geometry. The key tools include ↱CitySim Pro, ENVI-met, RayMan, Honeybee & Ladybug, Autodesk CFD, SOLWEIG, ↱TUF3D, CityComfort+, PALM-4U and SkyHelios (Table 2). Their application and selection depend on the ↱complexity of the urban environment, needed accuracy, and microclimatic variable of concern [1,47–67].↱

CitySim Pro is a validated stand-alone urban-scale energy and MRT simulation tool. It uses ↱Hoppe's integral radiation method with detailed

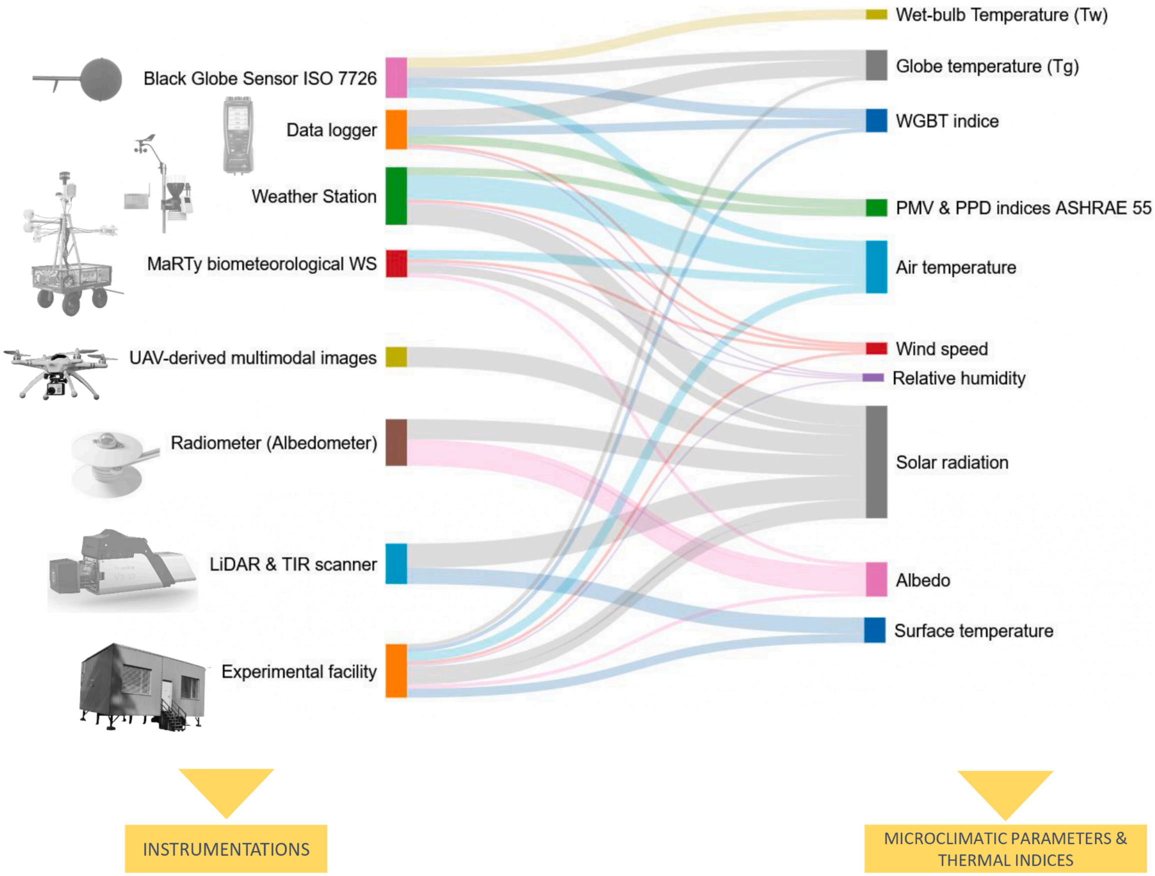

Fig. 3. Various instruments for MRT parameter measurements.

Table 1
MRT measurement instruments, dominant error sources, and appropriate application contexts.

Instrument type	Typical response time	Wind sensitivity	Radiation anisotropy captured	Dominant bias mechanism	Typical bias direction	Suitable applications	Limitation
150 mm Black Globe Thermometer	15–25 min	High	No (assumes isotropic field)	Thermal inertia; convective cooling influence	Underestimates rapid MRT peaks; overestimates under windy conditions	Steady indoor environments; long averaging periods	Unsuitable for dynamic outdoor environments
40 mm Black Globe	2–5 min	Moderate	No	Reduced inertia but still convectively sensitive	Improved peak detection but still lagging in transient shade–sun transitions	Semi-outdoor spaces; shaded courtyards	Cannot resolve second-scale fluctuations
Gray Globe (Reflectance = 0.3)	2–5 min	Moderate	No	Partial correction of solar absorptivity	Lower solar-driven overestimation compared to black globe	Outdoor comfort campaigns in sunlit environments	Still assumes isotropic radiation
Net Radiometer (Shortwave + Longwave)	Seconds	Low	Partial (direction aggregated)	Incomplete directional sampling	Underestimates asymmetry effects in canyons	Research-grade field studies; model validation	Expensive; requires calibration and correction algorithms
Six-Directional Radiometer / Cube Sensor	< 1 s	Very Low	Yes	Calibration error across faces; geometric simplification of body	More accurate directional flux representation	High-resolution outdoor mapping; validation of CFD/ LES tools	Higher cost; requires data processing expertise
Infrared Thermography (Surface-Based Estimation)	Instantaneous	Low	Indirect (surface-based)	Surface emissivity assumptions; reflection errors	Over/underestimation depending on material emissivity	Surface temperature mapping; urban diagnostics	Does not directly measure human radiative field
UAV / Drone Thermal Mapping	Seconds–minutes	Low	Indirect	Viewing angle bias; atmospheric correction	Context-dependent	Large-area urban MRT proxy mapping	Requires radiative model coupling

human geometry and radiative property ↱customization. CitySim Pro calculates sky and surface view factors based on ↱direct, diffuse, and reflected shortwave and longwave radiation, along with vegetation and ↱ground processes. Its strengths include the handling of complex geometries and detailed ↱surface properties, although it neglects longwave reflections, free-standing object ↱contributions, and local wind effects. The code is computationally demanding and requires ↱detailed input data and is therefore best suited to high-accuracy simulations of complex, ↱radiation-dominated environments [47–51].↱

ENVI-met is a comprehensive microclimate model directed at surface-plant-air interactions. It ↱employs Fanger's model to estimate MRT and incorporates the Indexed View Sphere (IVS) ↱for improved view factor accuracy. ENVI-met models sophisticated radiative exchanges, ↱including ground evaporation and vegetation transpiration, and is validated against field ↱measurements. It does simplify human geometry and building facades, lacks advanced ↱modeling of free-standing objects, and is computationally intensive [47,51].↱

RayMan is a fast-evaluation computer program for radiant fluxes and thermal comfort indices, ↱using Fanger's method and fish-eye photography in the estimation of sky and surface view ↱factors. It is easy to use and field-data validated but oversimplifies radiation exchanges with a ↱primary focus on ground reflections and longwave emissions [52,53].↱

Honeybee & Ladybug are open-source Grasshopper plugins that bring EnergyPlus simulations ↱and ray-tracing for MRT calculation. Longwave radiation is derived from EnergyPlus surface ↱temperatures, and shortwave adjustments utilize the SolarCal model. Both tools excel at ↱parametric modeling of complex geometries but depend heavily on the accuracy of ↱EnergyPlus outputs and neglect detailed vegetation and ground processes. Free-standing ↱objects are only accounted for in shading, not longwave exchanges [49].↱

Autodesk CFD uses finite element methods for thermal and fluid dynamics simulation and ↱computes MRT as a secondary outcome. It includes a flux-based approach with deterministic ↱view factors and presumes all surfaces to be diffuse grey bodies. While it has the capability to ↱simulate complex heat exchanges, Autodesk CFD is not validated for outdoor MRT, ↱simplifies material properties excessively, and ignores vegetation and ground processes, ↱limiting its use for outdoor comfort analysis.↱

SOLWEIG is a 2.5D model that calculates horizontal 2D MRT maps originating from Höppe's six-↱directional integral method. It successfully incorporates buildings and vegetation and represents human geometry by a standing cylinder shape and recent and ongoing improvements on certain radiations fluxes is taking place [53–57]. SOLWEIG is extensively validated against ↱field data [e.g., [53,56]].↱

TUF3D is a mesh-based 3D urban energy balance model that simulates radiative exchanges ↱and surface temperatures at high spatial resolution. It can model spatial-temporal MRT shifts ↱but is computationally intensive and limited by simplifications of human geometry and thus ↱not well-suited for direct comfort evaluations over large domains [58,59].↱

CityComfort+ is a more recent tool that is optimized for compact urban environments, ↱employing ray-tracing and human body projection area factors for shortwave radiation with a ↱simplified method for longwave exchanges. Although effective for high-rise environments, it ↱has not undergone extensive validation and does not include detailed modeling of vegetation ↱and surface-specific characteristics, making it less suitable for greener or more heterogeneous ↱urban environments [56–60].↱

Parallelized Large Eddy Simulation Model (PALM-4U) is a prognostic large-eddy simulation (LES) model for high-resolution urban climate and thermal exposure analysis, solving 3D prognostic equations for momentum, temperature, and scalars coupled with urban canopy modules (LSM, BSM, PCM, RTM v3.0). It employs an advanced radiative transfer scheme with ellipsoidal human body geometry for precise MRT calculation from directional shortwave (direct/diffuse, multiple reflections) and longwave fluxes [63,64].

SkyHelios is a diagnostic microscale model using the MOGRE graphical engine for spatial mapping of SVF, radiation fluxes, MRT, and thermal indices (PET/UTCI/PT) in complex urban areas via fisheye rendering of 3D vector geometries. It calculates detailed SW (direct/diffuse Valko anisotropic, fisheye reflections) and LW (Stefan-Boltzmann iterative Ts, sky emissivity) fluxes weighted by simplified human projection factors at 1.1 m resolution [65,66].

In summary, the choice of MRT modeling tool should be guided by

Table 2
Numerical tools for mean radiant temperature assessment.

	CitySim Pro	ENVI-met	RayMan	Honeybee & Ladybug	Autodesk CFD	SOLWEIG	TUF3D	CityComfort+	PALM-4U	SkyHelios
Developer	EPFL Solar Energy and Building Physics Laboratory (LESO-PB)	Michael Bruse	Andreas Matzarakis	Mostapha Roudsari & Chris Mackey	Autodesk	Fredrik Lindberg et al.	Krayenhoff and Voogt	Huang et al.	PALM Group	Andreas Matzarakis, Marcel Gangwisch, and Dominik Fröhlich
Mathematical Model	Integral radiation measurement by Hoppe (1992)	Bruse equation, derived from Fanger	Hoppe method; Fish-eye photo for SVF calculation	SolarCal model for shortwave, Man-Environment Heat Exchange Model 2005 for longwave radiation, Ray tracing for view factors	Finite Element Method (FEM), diffuse grey body model, deterministic view factors	Integral radiation measurement, to represent the human body as a standing cylinder compared to a box shape	Short and longwave radiation evaluated at mesh cells, MRT calculated from surface temperatures and view factors at each cell using integral radiation equations	Ray-tracing for short-wave radiation; Human Body Projection Area factor; lighting simulation software for short-wave; simplified longwave radiation model	Short and longwave radiation evaluated at mesh cells; MRT from surface temperatures and view factors using integral radiation equations	Diagnostic model using graphics engine MOGRE for fisheye rendering; radiation SW/LW fluxes via RayMan;
Degree of Accuracy	High (validated with BESTEST and EnergyPlus)	Moderately good accuracy validated against onsite measurements; overestimate daytime MRT	Moderately good accuracy, validated against on-site measurements but simplified assumptions limit accuracy, especially in complex contexts	Approximated predictions due to dependence on EnergyPlus surface temperatures; limited accuracy in vegetation and ground evaporation modeling	Low accuracy due to rough considerations of directional dependencies, wavelength, and surface properties; not validated outdoors	Validated against measurement; overestimation during shade, underestimation during sunlit conditions; errors at low sun elevations due to underestimated longwave emitted and shortwave reflected fluxes from facades	Moderately good simulation of temporal MRT shift but simplified assumptions limit accuracy in complex contexts	Not extensively validated; uses ray-tracing but lacks detailed human geometry modeling leading to simplified predictions of MRTs in complex scenarios	Moderately good simulation of temporal MRT shift; simplified assumptions limit accuracy in complex contexts	Validated SVF; radiation aligns with RayMan
Inputs to calculate MRT	Detailed 3D model of environment, global radiation, air temperature, relative humidity, wind speed, surface properties (albedo, emissivity), vegetation parameters	Global radiation, air temperature, relative humidity, wind speed, surface properties (albedo, emissivity), detailed 3D model of urban area, vegetation parameters	Global radiation, air temperature, relative humidity, wind speed, albedo, building/tree geometries, fish-eye photos for Sky View Factor calculations	Surface temperature (from EnergyPlus), view factors (from ray tracing), solar radiation data, and air temperature. 3D model of urban environment	3D geometry, surface properties, boundary conditions for solar radiation, material thermal properties	Global radiation data, air temperature, relative humidity, wind speed, surface albedo, 3D model of urban environment (sky-view factors), Digital Surface Model (DSM)	Urban geometry meshed into finite volumes, meteorological data, radiation fluxes, surface thermal properties	Urban geometry, global radiation, air temperature, humidity, Human Body Projection Area factor	Urban geometry meshed into finite volumes, meteorological data, radiation fluxes, surface thermal properties	3D vector geometry from shapefiles for buildings/trees (including height, albedo, emissivity, optical density), specified via SRID projection, with optional cloud cover
Body Geometry	Detailed, definable	Simplified, default values	Simplified, default values	Detailed	Simplified	Simplified	Simplified	Simplified	Simplified	Simplified
Shortwave Radiation	Detailed	Detailed	Simplified	Detailed	Simplified,	Detailed Anisotropic parameterization	Detailed	Detailed	Detailed	Detailed
Longwave Radiation	Detailed	Simplified,	Simplified	Simplified	Simplified	Detailed Anisotropic parameterization	Detailed	Simplified	Detailed	Detailed
Ref.	[47–51]	[47–51]	[52,53]	[47–51]	[47,48]	[53–57]	[58,59]	[60]	[55,56]	[57,58]

the built environment, required details, and microclimatic processes under consideration. High-accuracy tools like CitySim Pro, PALM-4U, SkyHelios and ENVI-met are suitable for complex, data-rich environments, while RayMan and SOLWEIG offer simplicity and quickness for preliminary evaluations. Honeybee & Ladybug provide flexibility for parametric studies, and Autodesk CFD and TUF3D are more fluid-thermal coupling focused but less detailed MRT analysis for outdoor environments.

2.2.5. *Predicting Mean Radiant Temperature under future urban climate scenarios*

Developments in modelling capabilities have enabled better communication across different scales with the potential to link the urban climate with local microclimate and Building Energy Models (BEM).

The Surface Urban Energy and Water Balance Scheme (SUEWS) model [68,69] is a local-scale urban land surface model, which can simulate urban radiation exchanges, energy, and water balances across neighborhood to city scales, and has been evaluated extensively across different cities and climates around the world [70]. Unlike CFD models, which require extensive simulation times, SUEWS can support year-long simulations with a grid cell down to 100x100m. Such a resolution allows evaluation of different urban configurations, integration of nature-based solutions (including water and green infrastructure) for microclimate research, and derivation of MRT from the SUEWS outputs. The development of Test Meteorological Year (TMY) for the neighborhood scale further allows integration with BEM models, which has been successfully demonstrated for different cities across the world and different simulation engines, such as EnergyPlus [71] and IES [72].

Resilience, however, necessitates that beyond current weather conditions (whether typical or extreme) climate change scenarios—alongside rising temperatures and the increased intensity and frequency of heat waves, and their corresponding impacts on urban environments— are adequately addressed. This requires the development and use of future weather files for the simulations for the areas under consideration. A comprehensive method to generate future weather files has been developed by the IEA EBC Annex 80 [73]: Resilient Cooling for Buildings using three time periods, the historical baseline (2001–2020), future mid-term (2041–2060), and future long-term (2081–2100) projections, for different cities and climate zones [74]. Along with urban densification scenarios and urban development configurations, such datasets can be employed to model the impact of adaptation and resilience scenarios on the urban microclimate and MRT for diverse needs, from heat stress assessments to buildings' energy use.

2.2.6. *Implications of hot summers and heat waves on mortality and morbidity in relation to Mean Radiant Temperature*

It is well known that exposure to heat extremes (including heat waves) pose a threat to human health and well-being. This risk is particularly pronounced in urban areas due to urban warming, and among older adults, who have a reduced ability to regulate body temperature and often face complications from existing health conditions [75,76]. Heat exposure is associated with elevated risk of cardiovascular disease-related mortality due to stroke and coronary heart disease, and morbidity due to arrhythmias and cardiac arrest and coronary heart disease [77].

Heat threshold and vulnerability to heat effects vary across different geographical and climate contexts, including disparities between cold and warm regions, coastal and inland areas, as well as local differences driven by urban features and tree canopy coverage [78,79]. For example, heat-related mortality occurs at lower temperature in cold regions than in warm regions [80]. Heat effects are also lower in locations close to the sea compared to inland locations [81] and in urban areas with high tree canopy coverage compared to areas with low tree canopy coverage. Differences in thresholds and vulnerability between populations depend also on differences in infrastructure (housing), culture and socioeconomic inequalities etc. [82].

During extreme heat events, characterized by warm, clear and calm weather conditions, the MRT is an essential meteorological variable influencing the heat load and thermal comfort of humans [1,83]. MRT has thus been used in some studies as a thermal predictor of heat-related mortality [84,85]. Thorsson et al. [82] showed that both high daytime MRT (>48°C) and nighttime MRT (>10°C) are associated with increased relative risk of heat-related mortality for all ages. For the oldest segment of the population (≥80 years), the risk is greater with high daytime MRT than with high nighttime MRT, whereas for ages 45–79 the risk is greater with high nighttime MRT. For the oldest segment of the population, the risk in mortality increases rapidly with increase daytime MRT, with a risk increase of 5% from 55°C and a risk increase of 10% from 59°C. Willers et al. [83] also showed that high daytime MRT is associated with an increased risk, with the population aged ≥ 85 years living alone at highest risk.

Whereas Thorsson et al. [82] showed that MRT is a much better thermal predictor of heat-related mortality than *Ta* in the Stockholm County, Sweden, Willers et al. [83] showed that *Ta* is a slightly better predictor than MRT and UTCI (universal thermal climate index) at the neighborhood scale in Rotterdam, the Netherlands. However, Willers et al. do not take variations in MRT into account as they do not consider variations in shadowing influenced by objects such as buildings and trees at the neighborhood scale examined.

Although the correlation between MRT, *Ta* and rational indices such as UTCI derived from the human energy balance is substantial [80,84,85], there are differences between the thermal predictors (e.g., number of meteorological variables included), which can explain their ability to predict heat-related mortality in the area considered. For example, in Stockholm, with limited cooling and mixing effect from wind on extreme heat events, the MRT is a much better predictor of heat-related mortality than Ta. However, in the coastal city of Rotterdam, where the cooling effect from wind is substantial even during extreme heat events, MRT (which does not include the effect of wind) is not superior to *Ta* and UTCI.

The results suggest that the ability of MRT as a predictor of heat-related mortality is geographical and climatological context-dependent. The results are in line with Morabito et al. [85], who showed that a thermal predictor including the effect of air temperature, air humidity and wind speed (i.e., the shade Apparent Temperature) reveals the best fitting with all-cause mortality among older adults (≥75 years) attributable to heat in the coastal city of Livorno in Italy, whereas a predictor including also the effect of solar radiation (i.e., outdoor apparent temperature) reveals the best fitting in the inland city of Florence. Moreover, results by Urban and Kyselý suggest that urban populations sheltered from wind are less vulnerable to the effect of wind than rural populations. Although UTCI has been shown to capture the thermal bioclimatic variability and relate such variability to the effects it has on human health [80,86,87], UTCI is never identified as the best thermal predictor of heat-related mortality over AT. This might be because UTCI tends to overestimate the wind chill effect, especially on days with extreme wind speed [88] and UTCI uncertainties in modelling MRT [89]. If all radiative fluxes are modelled based on synoptic observations, the uncertainty of UTCI in determining MRT may be up to ±6°C. This uncertainty may be critical under heat extremes.

In sum, there is no strong evidence (few studies with contradictory results) to favour the use of MRT over Ta or UTCI when studying heat-related mortality. Instead, it is suggested that the choice of thermal predictor should be based on geographical and climatological context of the area considered as highlighted by Morabito et al. [85]. In coastal and rural areas, it seems important that thermal predictors should include the cooling effect of wind (i.e., wind speed), whereas in inland urban areas it is important that they should include the effect of solar radiation (i.e., MRT). To be able to choose the best thermal predictor of heat-related mortality for a certain geographical and climatic context, however, more studies are needed.↱

2.3. Mean Radiant temperature and indoor environments

2.3.1. Influence of indoor environmental characteristics on variations in Mean Radiant Temperature

Indoor environmental characteristics exert a profound influence on MRT variations through multiple mechanisms, each intricately linked to building design, materials, spatial organization, and occupant activities. However, many indoor studies report a single MRT or operative temperature value and ignore spatial heterogeneity near glazing, radiant asymmetry, and transient solar patches, even though these dominate discomfort and drive cooling behavior.

One of the primary factors affecting MRT variability indoors is the choice of building materials. Furthermore, materials with high thermal mass, such as concrete or brick, absorb and slowly release heat, thus moderating MRT fluctuations over time. Conversely, lightweight materials like wood or gypsum panels exhibit rapid thermal responses to changes in internal or external conditions, resulting in more pronounced MRT variations. These dynamics critically affect occupant comfort, particularly in naturally ventilated or intermittently heated or cooled spaces [90,91]

Window placement and glazing characteristics play a significant role. Windows introduce direct solar radiation into indoor spaces, leading to localized zones with elevated MRT, commonly referred to as 'hotspots'. The orientation of glazing surfaces relative to solar paths, combined with properties such as solar heat gain coefficients and shading devices, modulates the intensity and distribution of radiant energy inside rooms. According to d'Ambrosio Alfano et al. [92], the radiative contribution from sunlit surfaces can substantially alter MRT, sometimes resulting in asymmetric conditions that foster local thermal discomfort.

Spatial organization also impacts MRT distribution by influencing air movement and temperature stratification. Poorly designed layouts can inhibit air circulation, causing thermal layers to form, especially in high-ceilinged spaces. This stratification leads to vertical gradients in MRT, where occupants may experience warmer air near the ceiling and cooler air at lower levels, complicating the overall perception of thermal comfort [93,94].

Surface finishes add another layer of complexity to MRT modulation. The emissivity and absorptivity of interior surfaces determine how much radiant heat is absorbed, emitted, or reflected. For instance, dark-colored surfaces with high absorptivity can significantly increase local MRT values when exposed to solar radiation, while reflective or light-colored surfaces might reduce local radiant heat effects. The study conducted by d'Ambrosio Alfano et al. [92] emphasizes that even slight differences in surface characteristics can alter measured MRT, impacting the accuracy of thermal comfort assessments.

Additionally, furniture arrangement and occupant activities introduce localized MRT variations. Furniture can obstruct or channel radiative and convective flows, leading to microclimates within the same room. Moreover, occupants themselves act as heat sources, with their metabolic heat contributing to localized warming. The activities performed whether sedentary or physically active further modulate this effect by influencing both convective and radiative exchanges [94,95].

In fact, the instrument choice must account for the specific indoor environmental characteristics to minimize uncertainty. Importantly, minor deviations in MRT measurement can substantially impact comfort indices like the Predicted Mean Vote (PMV) and the Operative Temperature (T_e). Their study revealed that variations within the ISO 7726 recommended accuracy range for MRT could shift PMV by ±0.16 to ±0.25, potentially altering the classification of a space's thermal environment. Consequently, environments assessed as thermally acceptable might, under different measurement approaches, fail to meet comfort standards, highlighting the sensitivity of indoor thermal perception to MRT variations. Moreover, thermal asymmetry common in rooms with uneven surface temperatures or direct solar penetration was shown to further complicate comfort evaluations. As d'Ambrosio Alfano et al. [92] demonstrated, asymmetries exceeding even a few degrees Celsius can cause localized discomfort.

In conclusion, indoor environmental characteristics strongly influence MRT variations through their effects on heat absorption, emission, reflection, and stratification. Therefore, understanding these interactions is critical for designing comfortable indoor environments and for the accurate assessment of thermal conditions. Given the challenges in MRT measurement and the sensitivity of comfort metrics to its variation, careful selection of materials, spatial organization, and measurement methodologies is essential.

2.3.2. Optimization of building design and HVAC systems to meet Mean Radiant Temperature requirements in current and future contexts

The choice and operation of HVAC systems in buildings have direct and significant ↱impacts on outdoor MRT. The most critical trade-off stems ↱from the waste heat rejected by air-cooled HVAC systems, particularly split units, ↱rooftop condensers, and chillers. These systems release sensible heat directly into the ↱surrounding air, heating nearby surfaces and increasing longwave radiation in outdoor ↱environments. This rise in surface and air temperatures elevates MRT, ↱worsening thermal comfort for pedestrians, especially in dense urban canyons where ↱radiative heat is trapped.↱

Studies in cities such as Berlin, Paris, Madrid, and Phoenix have demonstrated that ↱air-conditioning waste heat emissions increase outdoor air temperatures by 0.5°C to ↱over 2°C, which directly translates into higher MRT values. Elevated ↱surface temperatures from condenser waste heat intensify longwave radiation ↱exposure, increasing thermal stress on human bodies, particularly during heat waves ↱and nighttime when cities struggle to cool down.↱

A trade-off exists between air-cooled and water-cooled (or district-cooled) systems. Air-↱cooled systems, while inexpensive and easy to deploy, concentrate heat rejection ↱locally, drastically increasing surrounding MRT. Water-cooled systems, in ↱contrast, reduce local MRT peaks by moving heat to centralized cooling ↱towers or bodies of water. However, these systems demand higher infrastructure ↱investments and can shift environmental burdens by increasing water consumption ↱and potentially causing thermal pollution elsewhere.↱

Operational strategies of HVAC systems also influence MRT. For example, ↱load shifting or night cooling may reduce peak electrical demand but inadvertently ↱cause waste heat rejection during evening or early morning hours, when outdoor ↱public spaces are still in use. This can prolong the duration of high MRT ↱exposure in pedestrian areas, reducing urban livability.↱

Furthermore, even with high-efficiency HVAC systems, poor building envelope ↱design such as excessive glazing without shading-leads to increased indoor ↱cooling demands, thereby increasing outdoor waste heat and radiative stress. This ↱creates a vicious cycle where indoor thermal comfort is achieved at the expense of ↱raising outdoor MRT and worsening urban thermal conditions.↱

Future urban cooling strategies must explicitly target the reduction of outdoor mean ↱radiant temperature as a key performance indicator for thermal comfort and urban ↱health. Prospects include: ↱

- Predictive HVAC control and dynamic scheduling based on outdoor ↱MRT predictions, allowing systems to minimize waste heat during ↱periods of high outdoor thermal sensitivity.↱
- Hybrid cooling systems integrating radiative cooling materials and passive shading ↱to reduce the need for mechanical cooling and, consequently, the waste heat ↱that elevates MRT.↱
- Urban-scale MRT monitoring and modeling tools (CFD and radiation ↱balance models) to inform HVAC placement, operation, and city planning, ↱identifying critical hotspots influenced by condenser heat rejection.↱

- Urban design guidelines and regulations limiting surface temperatures and heat-↱releasing HVAC unit densities in public spaces to control MRT.↱
- District cooling systems combined with renewable energy and thermal storage to ↱centralize heat rejection away from pedestrian zones, effectively lowering urban ↱MRT and preventing local overheating.↱

By reframing cooling design and HVAC operations with outdoor mean radiant ↱temperature reduction as a central goal, cities can significantly improve outdoor ↱thermal comfort, mitigate UHI effects, and enhance public health resilience in a ↱warming climate.↱

2.3.3. Future perspectives for Mean Radiant Temperature research in the context of global climate change

As global climate change intensifies heat waves, accelerates urban densification, ↱and drives energy transitions, there is an urgent need to reframe MRT studies ↱beyond traditional static models and limited measurements. The future of MRT ↱research lies in multi-modal monitoring, AI-powered predictive modeling, integration ↱with nature-based solutions (NBS), and coupling indoor-outdoor environments to ↱protect citizens during extreme events.↱

MRT is emerging as a central parameter in the ↱assessment of urban climate conditions, particularly under the growing pressures of ↱global climate change. Unlike air temperature, MRT captures the complex interplay ↱of solar and thermal radiation from urban surfaces, making it a more sensitive ↱indicator of human thermal comfort and heat exposure in cities. With the increasing ↱frequency and intensity of heat waves, understanding, monitoring, and managing ↱MRT is no longer a purely academic pursuit but a critical component of climate ↱adaptation and public health strategies.↱

Traditionally, MRT studies have relied on isolated point measurements, often using ↱globe thermometers or limited field campaigns. While useful for controlled ↱experiments, such methods fail to capture the highly dynamic and spatially ↱heterogeneous nature of urban thermal environments. Recent advancements point ↱towards a future where MRT monitoring is conducted through multi-modal systems ↱that integrate satellite-based thermal imaging, long-term ground-based field stations, ↱drone-mounted thermal cameras, and dense IoT sensor networks distributed across ↱urban fabrics. These systems provide continuous, high-resolution data streams ↱capable of mapping MRT patterns in real-time, revealing not only the typical daily ↱cycles but also detecting emerging heat hotspots driven by urban growth or material ↱changes. Research demonstrates that combining these technologies greatly ↱enhances our capacity to assess and manage urban heat risks, offering cities the ↱tools to respond to changing thermal conditions with precision [96].↱

However, generating vast amounts of data is only one part of the solution. The next ↱frontier lies in transforming MRT modeling from static empirical frameworks into ↱dynamic, predictive systems powered by artificial intelligence and machine learning. ↱Traditional models, though robust for general analysis, often lack the flexibility to ↱account for the rapid changes in urban microclimates, especially under extreme ↱weather events. AI-enhanced models, trained on multi-source data, can forecast ↱MRT fluctuations hours or even days in advance. This capability opens the door for ↱real-time model predictive control (MPC) of urban cooling strategies, such as ↱activating shading systems, optimizing surface albedo, or deploying misting stations ↱during heat peaks. Studies have already demonstrated the potential of machine ↱learning models to accurately predict outdoor thermal comfort, balancing complexity ↱and computational efficiency, setting the stage for their integration into operational ↱city climate platforms [97].↱

Equally critical is the need to couple MRT assessments with the evaluation and ↱optimization of nature-based solutions (NBS) and their interaction with urban ↱energy systems. As cities invest in green roofs, urban forests, and water features, ↱quantifying their actual cooling potential under various climatic conditions becomes ↱paramount. The cooling performance of NBS is not staticit fluctuates with ↱vegetation health, seasonal changes, and long-term climate shifts. Moreover, ↱technologies such as air-source heat pumps and reflective materials, while ↱beneficial for energy efficiency, can alter the local radiant environment, potentially ↱increasing MRT. Future studies emphasize the value of machine learning to ↱identify optimal locations and configurations for NBS, ensuring maximum cooling ↱benefits without unintended consequences like radiative heat traps or vegetation ↱dieback [98]. Such integration ensures that urban climate ↱interventions are targeted, efficient, and resilient over time.↱

The human dimension of MRT is perhaps the most pressing, especially as extreme ↱heat events intensify. Exposure to elevated MRT is directly linked to increased heat ↱stress and health risks, particularly for vulnerable populations such as the elderly, ↱children, and outdoor workers. Yet, MRT has historically been treated as an outdoor ↱metric, disconnected from the indoor environments where people spend most of ↱their time. Future MRT research must bridge this gap, creating coupled indoor-↱outdoor models that assess total human thermal exposure. Integrating real-time ↱MRT monitoring into digital applications can empower citizens with personalized ↱heat alerts, guiding them toward safer routes or identifying nearby cooling centers ↱during dangerous conditions. AI-driven platforms will further enhance this capability ↱by dynamically activating urban cooling hubs or adjusting NBS based on forecasted ↱MRT thresholds, ensuring that protection measures are both timely and equitable [98,99].↱

For MRT to truly shape future cities, it must transcend scientific studies and be ↱embedded into policy, planning, and governance frameworks. Rather than ↱remaining a specialized thermal comfort metric, MRT should inform zoning laws, ↱building codes, and urban design guidelines. Tools like the Urban Multi-scale ↱Environmental Predictor (UMEP) exemplify how integrated modeling systems can ↱support such transitions, offering cities the capability to simulate and evaluate MRT ↱impacts of proposed developments or climate adaptation measures [100]. Standardized MRT monitoring and reporting will be essential for cross-city ↱comparisons, performance benchmarking, and ensuring that urban resilience ↱strategies effectively reduce radiative heat loads.↱

In conclusion, the evolution of MRT research reflects the broader transformation of ↱urban climate science from observational studies toward proactive, data-driven ↱management of urban thermal risks (Table 3). The integration of high-resolution multi-modal ↱monitoring,

Table 3
Old vs. future MRT perspectives.

Aspect	Old Perspectives	Future Perspectives
Measurement Approach	Globe thermometers, manual campaigns	Multi-modal: satellites, long-term stations, drones, IoT sensors [98–100]
Resolution (Spatial/ Temporal)	Low, sporadic	High-resolution, real-time, continuous [100]
Modeling Approach	Static empirical models (RayMan, SOLWEIG)	AI/ML-enhanced predictive models with real-time forecasting [56]
Validation	Rare or single-point validation	Continuous calibration with multi-modal data streams [98]
Energy System Coupling	MRT separate from energy fluxes	Coupled MRT-energy modeling (including heat pumps, cooling) [97,101]
Nature-Based Solutions	Generic green assumptions	AI-optimized NBS deployment [99,102] based on MRT impact
Indoor-Outdoor Coupling	Mostly outdoor focus	Indoor-outdoor integration for citizen health and apps [103–105]
Health & Safety Focus	General comfort assessment	Real-time citizen alerts, cooling hubs activation [105]
Decision-Making Role	Research only	Embedded in urban planning, codes, early warning systems [106,107]

AI-enhanced predictive modeling, dynamic control of nature-based and ↱technological interventions, and a citizen-centric approach to health and safety ↱marks a paradigm shift in how cities engage with their thermal environments. By ↱embedding MRT into climate adaptation policies, planning regulations, and digital ↱tools, cities will be better equipped to protect their populations, optimize their built ↱environments, and build resilience against the intensifying impacts of global climate ↱change.↱

3. Recommendations and conclusions

3.1. Operational implementations and future practical and research directions for MRT

This review comprehensively examines MRT applications across urban climate, architectural design, and health domains. Cross-domain synthesis reveals that these fields converge on MRT as a core radiative heat exposure indicator while diverging in methodological priorities and optimization strategies. Urban-scale studies emphasize spatial variability and morphology-based mitigation through nature-based solutions; building-scale research prioritizes material properties, envelope design, and HVAC integration; health-oriented investigations focus on exposure thresholds and vulnerability assessment. A fundamental gap emerges from this analysis: despite universal reliance on MRT as a unifying parameter, methodological harmonization and integrated frameworks for translating findings across scales remain underdeveloped. Addressing this gap requires standardized assessment protocols and cross-disciplinary modeling approaches capable of bridging design, climate, and public health applications.

Overall, operationalizing MRT in urban planning and building development requires a multi-dimensional approach integrating technical, policy, and social strategies. Technically, cities must embed seasonal MRT maps into GIS-based zoning and local climate assessments, establish clear and local MRT thresholds for pedestrian comfort within design guidelines, and mandate heat mitigation measures including shading, high-albedo materials, and vegetation in new developments and retrofits. At the policy level, MRT should be integrated into heat-risk management plans to identify priority intervention zones and guide strategic implementation of cooling infrastructure and green corridors, with cost-benefit analyses informing investment decisions. Moreover, policymakers must address social barriers: unequal heat exposure, limited public awareness, and resistance to design operations require community engagement, equity-centered planning, and participatory decision-making processes. Simultaneously, deploying simplified monitoring networks and standardized modeling workflows will enable routine MRT assessment, transforming radiative heat exposure into a measurable performance metric for climate-resilient and health-oriented urban and building policies.

3.2. Main findings of the review

This paper examines the crucial impact of the MRT in evaluating thermal conditions, addressing ten key domains. The findings determined that MRT is a critical microclimatic parameter in thermal behavior, representing the most dominant component influencing human heat balance and human thermal comfort (D1). Furthermore, it is highly recommended to introduce MRT long-term assessment as key strategy for the urban planning and landscape design early stages (D2). In this regard, elevated MRT amplifies significantly human thermal stress and urban heat island intensity, thereby escalating physiological heat strain and augmenting energy demand (D3). Thermal measurement protocols utilize conventional globe thermometers and advanced instrumentations like six-directional sensors, infrared thermography, and UAV-based systems offer scalable MRT assessment with high accuracy (D4). Additionally, numerical models and software such as ENVI-met, CitySim Pro, SOLWEIG, RayMan, PALM-4U, SkyHelios and Honeybee/Ladybug are recommended as effective tools to simulate MRT under varied weather conditions with distinct spatial configurations, radiation handling, and resolution (D5). A methodological prediction of MRT requires coupling urban models like SUEWS with Building Energy Models and climate-projected weather files, enabling assessment of adaptation strategies across temporal horizons and urban configurations (D6). Despite the strong relationship of MRT to outdoor environments, it substantially impacts indoor thermal comfort and cooling loads, particularly through window placement, solar gain, and building material properties (D7). Elevated MRT during heat events, which have increased remarkably in recent years, correlates with elevated morbidity and mortality, especially among vulnerable populations, emphasizing its crucial role in heat-health risk mapping and awareness systems for urban policies and decision makers (D8). Therefore, by reframing cooling design and HVAC operations with MRT reduction, cities can significantly improve outdoor ↱thermal conditions, mitigate UHI effects, and enhance public health resilience in a ↱warming climate (D9).↱ Overall, future MRT research should prioritize high-resolution dynamic monitoring, cross-scale integration with health models, and embedding MRT in regulatory frameworks and policy reports (D10).

Table 4 presents a comprehensive synthesis of critical knowledge gaps, methodological bottlenecks, and minimum reporting standards essential for reproducible and comparable MRT research. Moving beyond thematic synthesis, this framework conducts a methodological audit of each domain, systematically identifying what current studies omit, why these omissions persist, and which specifications are essential for enabling cross-study validation. The formalized requirements establish baseline standards that address the pressing need for enhanced reporting structure, transparency, and analytical rigor in MRT-related research.

CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Given their roles as editors and associate editors of the journal, Bao-Jie He, Andreas Matzarakis, and Ayyoob Sharifi had no involvement in the peer-review of this article and has no access to information regarding its peer-review. Full responsibility for the editorial process for this article was delegated to another journal editor. If there are other authors, they

Table 4
Critical knowledge gaps, methodological bottlenecks, and minimum reporting standards across MRT research domains.

Domain	Systematic gaps	Methodological bottleneck	Review insufficiency	Minimum reporting requirement
1. MRT as microclimatic parameter vs. thermal index	Studies conflate MRT with composite thermal indices without isolating the radiative contribution.	Lack of explicit separation between radiative and convective components	Reviews summarize indices but do not audit how MRT is independently derived.	• Explicit MRT equation used • Separation of radiation vs. air temperature effects • Thermal index formulation and inputs disclosed
2. MRT in outdoor urban environments	Spatial heterogeneity of radiation fields is underrepresented.	Limited directional radiative sampling and oversimplified sky view assumptions.	Reviews describe urban design impacts but lack flux-level quantification.	• Sky View Factor (SVF) method reported • Shortwave vs. longwave flux separation • Measurement height and exposure state stated
3. MRT, UHI, and thermal comfort interaction	Non-linear coupling between MRT and UHI intensity is rarely modeled.	Coarse temporal resolution and absence of nocturnal radiation analysis.	Reviews treat UHI as air-temperature driven rather than radiation-driven.	• Day/night MRT differences • Anthropogenic heat inclusion method • Thermal index comparison under similar conditions
4. MRT measurement instruments	Instrument response lag and wind bias are systematically ignored.	Dependence on globe thermometers with isotropic radiation assumptions.	The reviews list instruments without bias quantification.	• Instrument type and diameter • Response time and wind correction method • Solar exposure condition documented
5. Numerical MRT modeling tools	Validation against field measurements is inconsistently reported.	Divergent human body geometries and radiation algorithms across tools.	Reviews compare features but not uncertainty propagation.	• Radiation model type (ray-tracing, integral) • Human geometry assumption • Validation metrics (RMSE, bias, sample size)
6. MRT & future urban climate scenario prediction	Future weather files rarely incorporate radiation anisotropy shifts.	Downscaling climate projections to the microclimate scale remains weak.	Reviews discuss climate change qualitatively without exposure quantification.	• Climate scenario (baseline, mid, long-term) • Weather file generation method • Urban morphology scenario assumptions
7. MRT and mortality/ morbidity	Context-dependency of MRT as a predictor is insufficiently addressed.	Confounding between wind, humidity, and radiation is not statistically isolated.	Reviews compare predictors but lack methodological harmonization.	• Predictor comparison framework (Ta, UTCI, MRT) • Population vulnerability segmentation • Geographic/climatic classification disclosed
8. Indoor MRT variability	Radiant asymmetry and solar patch effects are underreported.	Limited multi-point indoor radiative sampling.	Reviews focus on comfort indices rather than radiant field structure.	• Surface emissivity and glazing properties • Radiant asymmetry quantification • Measurement grid and height specification
9. HVAC systems and MRT	Outdoor waste heat contribution to MRT is rarely quantified.	Separation of building energy modeling from microclimate radiation modeling.	Reviews assess energy efficiency without radiative externalities.	• Waste heat rejection rate (W/m^2) • HVAC system type and cooling strategy • Outdoor MRT measurement/model linkage
10. Future MRT research and AI integration	Data-driven prediction lacks standardized validation protocols.	Fragmented datasets and inconsistent sensor calibration.	Reviews promote AI potential without defining reproducibility criteria.	• Data source and calibration protocol • Training/validation split disclosure • Error metrics and uncertainty bounds

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

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