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Review

Modelling the impact of irrigated vegetation on urban microclimate: A review

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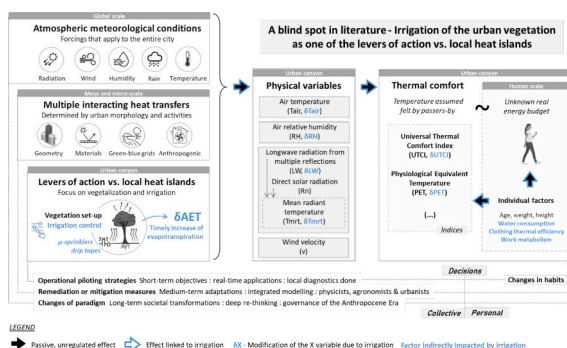
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HIGHLIGHTS

- Review of the components, architecture and assumptions of urban microclimate models
- Methodologies and numerical models to handle street-scale microclimatic variables
- Model validation issues and solutions for determining physical processes
- Recommendations to provide reliable values for thermal comfort indices
- The role of irrigation in enhancing the cooling effects drawn from urban vegetation

GRAPHICAL ABSTRACT



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ABSTRACT

The repeated occurrence, intensity and frequency of urban heatwaves pose significant challenges to urban areas. This paper critically reviews the current state of modelling the impact of irrigated vegetation on urban microclimate. It synthesizes findings from recent publications on the subject, focusing on the methodologies, challenges, and advances in numerical models that describe thermal comfort and heat mitigation strategies. Emphasizing the need for a transdisciplinary approach, the review highlights the key thermal and water-related factors influencing urban microclimates, including aerodynamic, radiative and phase change (e.g. evapotranspiration) processes, in interplay with urban geometry, materials and vegetation, especially when irrigated on purpose. The paper categorizes existing models based on their applications, physical modelling capabilities, and spatial-temporal discretization, offering guidelines for model selection tailored to specific urban planning objectives. Additionally, it provides a detailed description of the most pertinent models, especially regarding vegetation modelling for urban areas. The review underscores the necessity of validating existing models and the

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need for a standardized validation method for urban climate models. Future research directions are proposed to enhance the integration of vegetation effects in urban climate models, optimize irrigation strategies, and improve the predictive accuracy of these models to support sustainable urban design and policy-making.

1. Introduction

The multiplication and intensification of heatwaves and their significant impacts in urban environments is a direct consequence of global warming and urbanization, causing increased discomfort, health issues and fatalities in cities (Nazarian et al., 2022). This topic has gained significant attention from multiple disciplinary fields exploring urban climate controls (Kim and Brown, 2021). With 2023 being the hottest year on record (Perkins-Kirkpatrick et al., 2024), persistent heatwaves have severely impacted urban ecosystems, causing infrastructure failures, productivity loss, social instability, and disruptions in services (Barriopedro et al., 2023). Increased political and societal awareness have raised the need for informed, integrated management decisions, necessitating a holistic modelling approach (Bogdanovich et al., 2023; Klingelhöfer et al., 2023; Mauree et al., 2019). According to a wide consensus in the literature (Klingelhöfer et al., 2023; Taghvaie et al., 2023; Vurro and Carlucci, 2024) it is necessary to (i) evaluate heat transfers in urban environments, (ii) identify potential levers to mitigate heatwaves, then (iii) assess the relevance of envisioned mitigation measures for current and future climates.

The study's temporal horizon dictates the type of solutions, from short-term strategies to long-term transformations. Spatial and temporal scales guide the choice of indicators for mitigating climate change intensification (Schlünzen et al., 2011). Combined, spatial and temporal dimensions support positioning urban environment models, particularly urban microclimate models (Scherer et al., 2019). According to Zhou et al. (2022), these are the scales at which technical means, proper design and relevant resource management may allow regulating the local climatic conditions, creating a virtuous circle and positive feedback loops between local decisions taken (resource consumption) and local effects observed (temperature decrease). Therefore, the sustainability and resilience of a city are directly influenced by actions taken to manage its local climate (microclimate). However, despite the growing urgency of implementing concrete adaptation measures, a critical question remains: do existing theoretical frameworks and numerical models provide sufficient guidance for decision-making across the diverse stakeholders involved? Regardless of the spatial and temporal scales of interest, denoting the length, width, height and duration of the urban scene to describe, modelling urban environments is complex as it must integrate aerodynamic, thermal, hydric and radiative phenomena influenced by urban geometry, materials, and multiple heat sinks and sources, including anthropogenic heat production.

Urban climate studies can be categorized by scale: (i) mesoscale (20–200 km), (ii) local scale (100 m–50 km), and (iii) microscale (1 mm–1 km) (Oke et al., 2017). Mesoscale models focus on the development of the Urban Boundary Layer resulting from interactions between atmospheric flows and the urban surface, mostly used for weather and air quality forecasting (Martilli, 2007). Nevertheless, the high computational costs of large-scale modelling prevent any explicit description of the subscale processes, at the need of accounting for them via apparent or effective parameters (Oke et al., 2017). Local and microscale models are keener on capturing the explicit interactions between urban and environmental variables, requiring detailed modelling of momentum, energy, and mass flows. These models are classified into Computational Fluid Dynamics (CFD), Energy Balance Models (EBM) and Building Energy Simulation (BES). CFD models use transport equations like the Navier-Stokes equations (Toparlar et al., 2017) while EBM solve energy conservation equations for 2D or 3D urban surfaces (Oke et al., 2017). BES models analyze energy usage and environmental fluxes at the building scale. Most models can also be coupled or chained to study

urban climatology, analyze the current urban environments, or run scenarios for development projects. Despite their advantages, the multiplicity of modelling approaches raises a fundamental question: how should the most appropriate model be selected for specific applications such as water resource management, energy efficiency, air quality, public health, and thermal comfort enhancement?

Given the complexity of urban thermal environment analysis and the diverse objectives that can be pursued, this study focuses on the microclimatic scale, where interventions directly impact individuals, particularly pedestrians, with the joint effect of climatic conditions and human interventions on thermal comfort perceived by citizens (Ullah et al., 2024). The primary, smaller urban scale for microclimatology studies is indeed the urban street canyon, where thermal performance indicators for adaptation strategies include bio-meteorological variables (such as air temperature, wind speed, mean radiant temperature) and thermal comfort indices (Li and Liu, 2020; Shoosharian et al., 2018). The most popular of these indices are the Physiological Equivalent Temperature (PET, (Höppe, 1999)) and Universal Thermal Climate Index (UTCI, (Bröde et al., 2011)). While meteorological descriptors are objective measurements, thermal comfort indices assess the human perception of environmental factors as a whole, aiming to minimize subjectivity for daytime analyses (Yang et al., 2019). These indices represent the temperature felt by individuals, assessed from multiple, variably weighted physical variables of the urban scene. Thus, they should be seen as outcomes of integrated, context-dependent modelling. Their simplicity aids in comparing local climate regulation efforts, but their values should only be documented as the result of an explicit series of hypotheses and interdependencies between variables, with uncertainties affecting them (Elnabawi and Hamza, 2019) (Fig. 1). While these indices provide a useful synthesis for comparative assessments, their application in complex urban settings is subject to limitations. The UTCI, although regarded as one of the most comprehensive indices, is constrained by its operational validity range: air temperatures between $-50\text{ }^{\circ}\text{C}$ and $+50\text{ }^{\circ}\text{C}$, mean radiant temperature between $30\text{ }^{\circ}\text{C}$ below and $70\text{ }^{\circ}\text{C}$ above air temperature, wind speeds at 10 m height between 0.5 and 17 m s^{-1} , and relative humidity up to 100 % (Grosdemouge, 2020; Jing et al., 2024). These constraints can limit its reliability under extreme or highly variable microclimatic conditions, such as those found in densely built urban areas. PET, on the other hand, tends to be less accurate under high solar radiation, often failing to capture thermal discomfort in exposed environments (Jing et al., 2024).

Attempts to influence the temperatures felt have indeed been very diverse (Nasrollahi et al., 2020). Mitigation strategies at the microclimatic scale tend to favour place to the presence of urban vegetation, due to its ease of implementation and adaptability to different urban environments and the potential to mitigate bio-meteorological parameters and thermal comfort indices, while also enhancing urban ecosystem services (Nasrollahi et al., 2020).

Numerous studies have shown that vegetation's cooling effect is linked to irrigation (Cheung et al., 2022a, 2022b; Livesley et al., 2021; Mballo et al., 2021). However, the need to irrigate without depleting urban water resources is a challenge (Mauree et al., 2019). This underscores the importance of modelling approaches to support decision-making and optimize water allocation, particularly at the street canyon scale where microclimatic impacts are most pronounced (Fu et al., 2022). With water scarcity intensifying—especially in arid and Mediterranean regions where urban vegetation is critical for thermal regulation—numerical models must accurately represent both the benefits of irrigation and the impacts of water stress (Pan et al., 2023; Reyes-Paecke et al., 2019). Evidence from recent studies also suggests that

current irrigation practices are often excessive, indicating that expanding urban vegetation may be feasible without increasing water use, provided more efficient irrigation strategies are employed (Coutts et al., 2013; Guo et al., 2021; Reyes-Paecke et al., 2019).

This critical review considers the last six years of research in the field (current model types, components, structure and assumptions, methodologies followed and validation issues) before discussing perspectives of improvements and providing recommendations, especially to assess the cooling effects obtained from irrigation of the urban vegetation on microclimate.

2. Objectives and database

The current Informatics Era is marked by the accelerated development of sensors and facilities for data acquisition, storage, interpretation and analysis — the latter increasingly supported by computational fluid dynamics simulations, energy balance models, and artificial intelligence (AI) techniques such as machine learning and data-driven modelling (Asadi et al., 2020; Gobakis et al., 2011; Tanoori et al., 2024). When properly used, these are expectedly prone to feed and inform sustainable and resilient resource management scenarios, for the well-being of citizens having to face heatwaves in urban contexts. However, this requires both, and successively, understanding the processes at play (passive knowledge, Section 3, Tables 1 and 2) and being able to significantly act upon them (active know-how, Section 4). This two-stage procedure provides the frame, logic and objectives of this paper.

The search equation used on the Web of Science (WOS) database was (Street canyon OR Urban Street OR Urban canyon) AND (Vegetation Simulation OR Plant model OR Irrigation OR Water balance) AND (Numerical Simulation OR Numerical Approach OR Model*) AND (Thermal Comfort OR UTCI) covering the period between 2018 and 2023. This literature review covers the past six years to identify the most widely

used numerical models in their latest versions, ensuring a dataset large enough to encompass a broad range of models while remaining manageable for comprehensive analysis by the research team. All retrieved articles were downloaded, and an initial screening of abstracts, methodologies, and conclusions was conducted to classify the material appropriately. As a result, 517 studies have been identified, of which 56 % were articles fully within the scope (numerical models likely able to deal with the impact of the local vegetation, via irrigation or not, on the microclimatic conditions), 4 % were literature reviews on microclimate models, 1 % were not found or behind paywalls, and 39 % were still out of scope, i.e., not filtered out precisely enough before further examination. Fig. 2a depicts those results with more details.

In the following, the 19 review papers found will be confronted to assemble a comprehensive view of current modelling practices and identified challenges, in describing the local link and feedbacks between urban vegetation properties and microclimatic variables. The 273 sources responsible for 56 % of the ‘Microclimate models describing the impact of vegetation’ worked with 22 different numerical models, which are listed in Fig. 2b.

While an initial attempt was made to extract and synthesise reported vegetation cooling effects, as well as to assess the efficiency and accuracy of numerical models in representing these effects, the considerable heterogeneity in modelling approaches, vegetation typologies, boundary conditions, and validation criteria prevented the identification of consistent quantitative trends. As such, the review focuses on comparisons of model capabilities, assumptions, and applications, providing insight into which approaches may be best suited to particular research or planning contexts.

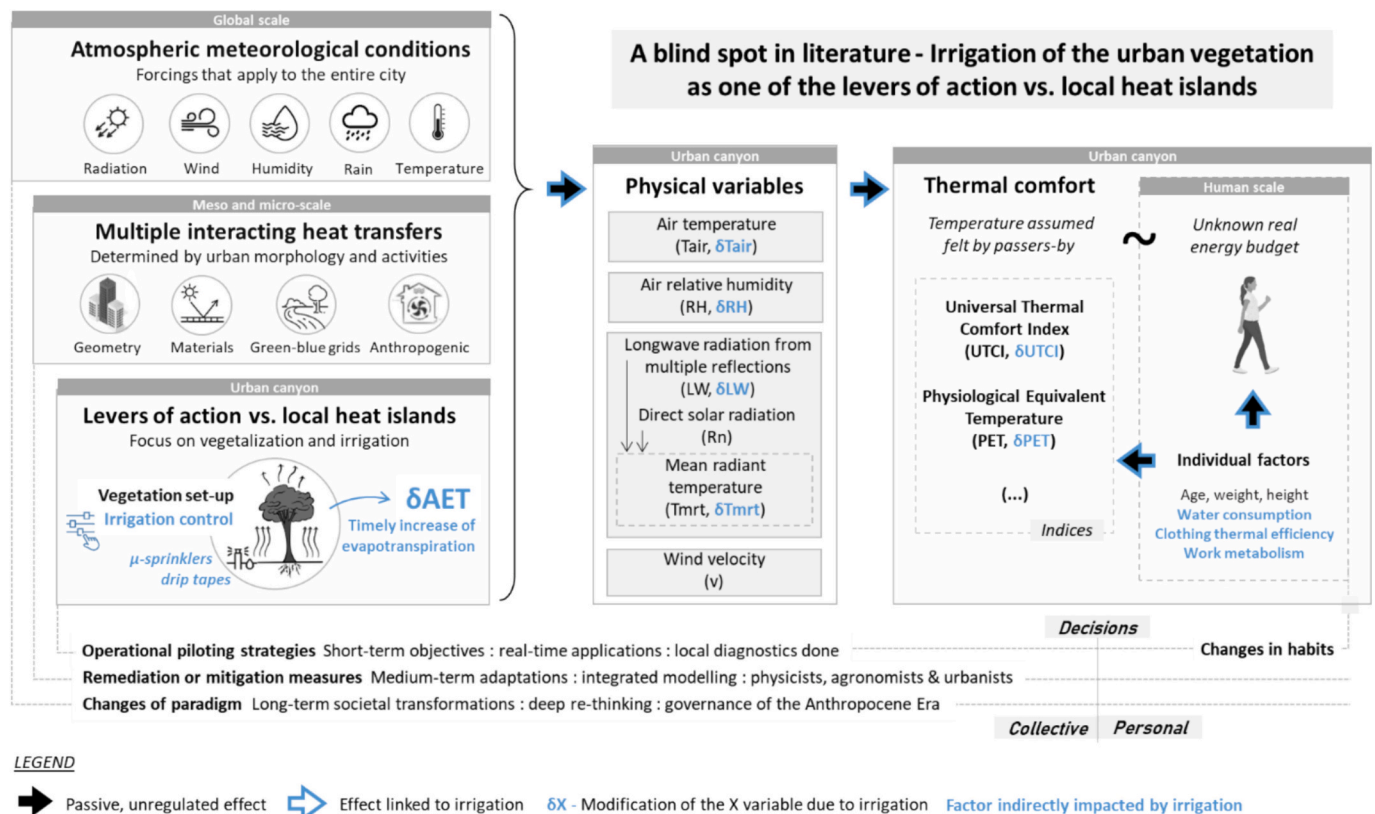


Fig. 1. Summary of synergies between the different urban scales and the elements that make them up connected with the variation of thermal comfort indices at the urban canyon scale, based on irrigation strategies for the urban vegetation.

Table 1

Literature review articles identified with the search equation on the Web of Science database addressing “urban climate modelling” and “morphology”. References in order of citation in [Section 3.1.1](#).

Reference	Main focus
(Lam et al., 2021)	Numerical simulations of outdoor thermal environment, validation vs. observed air and mean radiant temperature. Mitigation sought in urban geometry, vegetation, and surface materials. Calls for climate change impact and multi-scale studies.
(Mauree et al., 2019)	Software tools in which urban climate, energy demand of the urban space and outdoor comfort are treated separately. Highlights the need for a holistic approach of urban processes. Suggests a comprehensive framework to design low-carbon and resilient cities.
(Krayenhoff et al., 2021)	Mitigation strategies from numerical modelling, relying on green-blue infrastructure and reflective materials. Metrics of cooling effectiveness (microscale, mesoscale). Recommendations for optimal design of heat mitigation strategies.
(Dey and Joshi, 2023)	Advancements and challenges in experimentally validated modelling of microscale urban thermal environments, aiming to improve the accuracy of urban heat mitigation strategies, and confidence in them.
(Hassan, 2023)	Urban microclimate performance (outdoor thermal comfort, air quality, solar radiation, acoustics comfort, and urban energy) and numerical methods, application fields, opportunities and possibilities of CFD-based models, energy balance models, data-driven models and coupled models.
(Lauzet et al., 2019)	Reviews methods to incorporate urban microclimate into Building Energy Models (BEMs), discusses microclimate and building models, coupling approaches, and differences in simulation outcomes.
(Fischereit and Schlünzen, 2018)	Reviews thermal indices for outdoor thermal comfort assessment with obstacle-resolving models (ORM). Identifies criteria and features for suitability. Provides guidance for selecting appropriate indices for ORM-based thermal comfort studies
(Yang et al., 2023)	Recent advancements in urban microclimate research, covering traditional methods (field measurements and wind tunnel modelling) and emerging approaches (CFD simulations, artificial intelligence, data-driven models and satellite).
(Zhao et al., 2022)	Examining airflow distributions around buildings via wind tunnel tests. Reviews techniques, instruments, and findings for various building configurations, highlighting need for wind tunnel testing in building design and challenges.
(Zhao et al., 2023)	Experimental studies (multiscale, multi-physics) in similitude works for solar radiation absorption, thermal buoyancy effects, pollutant dispersion. States challenges: integrating anthropogenic processes, combining fluid tunnels with in-situ studies.
(Zhao et al., 2020)	Impact of urban street canyon flows (isothermal, non-isothermal) on microclimate, pollutant dispersion, and thermal comfort. Integrates theoretical, experimental, and numerical aspects. Identifies critical points and challenging questions.
(Wu et al., 2022)	Impacts of green infrastructure on elderly care centres, discussing benefits for air quality, thermal environments, and design logics. Calls for holistic design recommendations and to assess social and economic impacts.
(Wankhade et al., 2023)	Describes air displacement in urban layouts and street canyons, to assess a “ventilation potential”. Provides a state-of-the-art of experimental and numerical methods, approaches and case studies in the last 30 years.

3. Microclimate models

3.1. Review of methodologies

3.1.1. Methodologies and challenges for urban microclimate modelling

Understanding the multifaceted physics inherent to urban areas is crucial to assess various strategies to improve thermal comfort at the

Table 2

Literature review articles identified with the search equation on the Web of Science database addressing “mechanisms and modelling approaches for urban green infrastructure”. References in order of citation in [Section 3.1.2](#).

Reference	Main focus
(Yang et al., 2019)	Simulates outdoor microclimate as influenced by vegetation effects. Summarizes the strengths and weaknesses of current vegetation models and performance indices. Illustrates model principles, technical recipes, and related software.
(Ernst et al., 2022)	Relates urban greening strategies’ impact on microclimate and air quality, within the urban canopy layer, through bibliometric analysis. Reveals limited collaboration between microclimate and air quality fields.
(Zhu et al., 2023)	Investigates urban green infrastructure effects on urban heat island mitigation and energy demand reduction through numerical simulations, aiming to enhance integration with building energy models.
(Broadbent et al., 2019)	Assesses the capability of TARGET, a user-friendly model, for evaluating the cooling impacts of green and blue infrastructure on urban temperatures.
(Zheng et al., 2023)	Analyses heat and moisture exchange in canopies, validation of thermal simulations, and environmental benefits of urban trees. Cites future opportunities: real-time measurements in parallel with more accurate 3D models.
(Tsoka et al., 2018a)	Assesses the capabilities of ENVI-met for urban microclimate studies and to evaluate mitigation strategies, with a focus on urban greening and “cool materials”.

microclimatic scale (Lam et al., 2021) and project their effects for future conditions (Mauree et al., 2019) including informed, well-thought urban designs (Krayenhoff et al., 2021). Overall, geophysical fluid flows can be described with the traditional fluid dynamics equations for mass, momentum, and energy conservation, assuming Newtonian and incompressible flows, where radiative heat transfer is coupled to the energy equation using radiation models (Dey and Joshi, 2023). A known difficulty is that flow characteristics are highly sensitive to small-size turbulence patterns (e.g. forced convection) and anthropogenic heat release (e.g. free convection) in urban environments (Dey and Joshi, 2023). To effectively model these features, additional turbulence equations can be coupled to the conservation equations using turbulence models, typically Large Eddy Simulations (LES), and Reynolds-Averaged Navier–Stokes (RANS) within urban canyons (Dey and Joshi, 2023).

Various methodologies are available for urban microclimate modelling (Hassan, 2023), resorting to different types of models thus families of approaches (CFD, EBM, data-driven models, coupling approaches, Fig. 3). CFD models discretize the Navier–Stokes equations (or parent formulations) to solve mass, momentum and heat transfer with the help of additional turbulence models, using numerical methods (finite differences, finite elements or finite volumes). This offers the opportunity of explicit, coupled simulations between flow models (velocity and temperature fields), source-sink terms (humidity and energy production or absorption) and geometric, textural descriptions (flow boundaries, either plain or porous). Such approaches rely on fine domain discretization thus allow high spatial and temporal resolutions for studying urban green and blue infrastructures. EBM apply energy conservation principles within a control volume to manipulate wind-induced phenomena around large-size obstacles, and can integrate urban canopy models for energy budget purposes. Data-driven models use large datasets and apply statistical or AI techniques to associate characteristics with end-uses, with machine learning and statistical methods being commonly used. Finally, the external coupling (or chaining) of software has recently been proposed between models operating at different but overlapping scales (e.g. BES informed with urban microclimatic data) or to work at a given scale but with different types of flows, as in the case of SOLENE-microclimat, coupling code-saturne (CFD) and SOLENE (EBM) (Hassan, 2023; Lauzet et al., 2019).

As detailed by Dey and Joshi (2023) while only high-level approaches are potentially able to reproduce results with high precision,

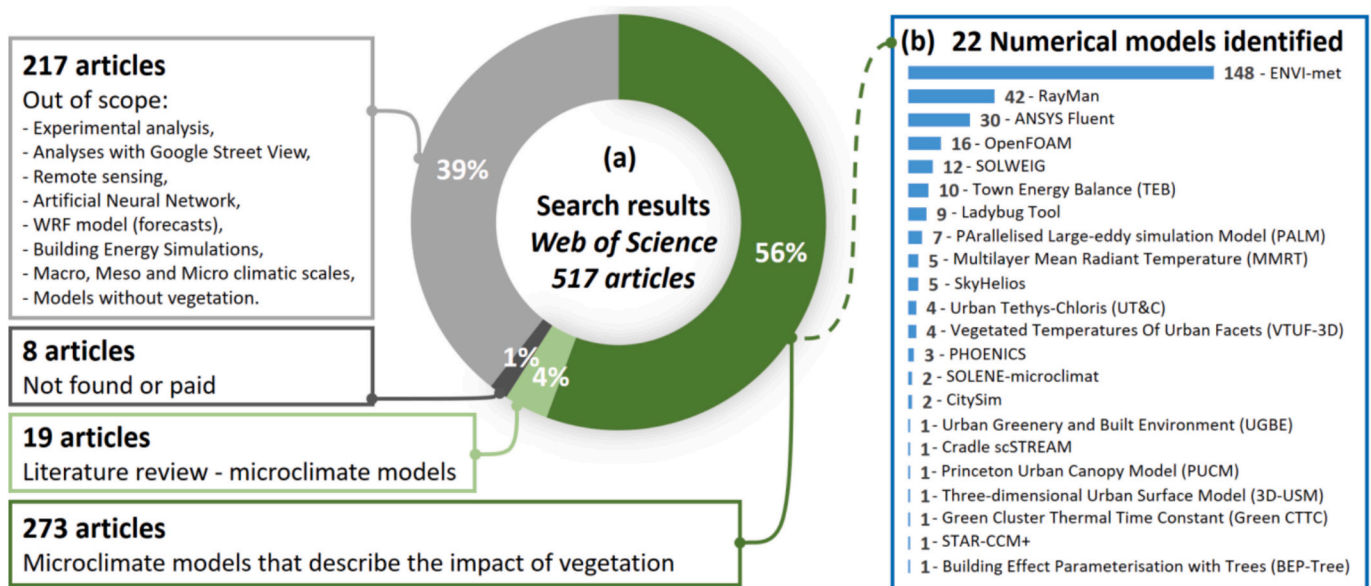


Fig. 2. (a) Search results on the Web of Science: 517 articles found, of which 39 % (217 articles) were out of scope, 1 % (8 articles) were either unavailable or behind paywalls, 4 % (19 articles) were literature review articles, and 56 % (273 articles) contained information regarding microclimate models that describe the impact of vegetation. (b) The 273 articles dealing with microclimate models that describe the impact of vegetation mentioned 22 numerical models, whose names and number of citations appear in the bar graph.

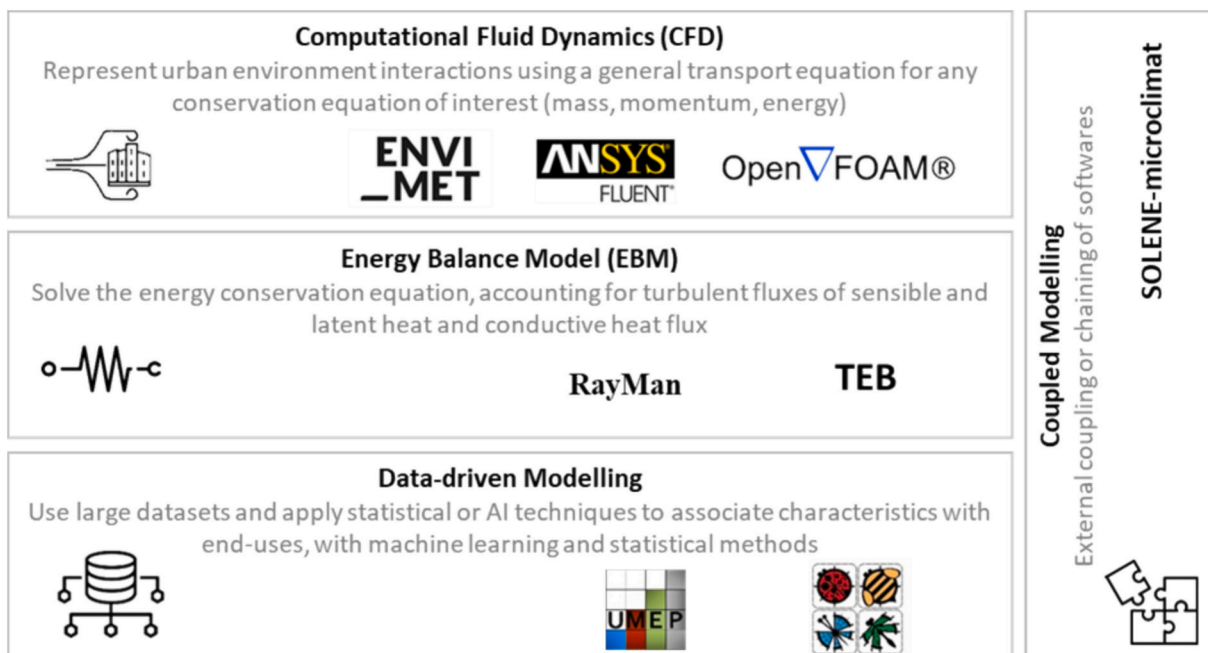


Fig. 3. Methodologies for urban microclimate modelling, showing the three main families of approaches present in the literature as well as their possible coupling.

stability and consistence, validation is far from straightforward and requires dedicated procedures. First, ensuring that the simulation is discretized so as to ensure independence between the spatial and temporal steps, especially for transient modelling (Section 4.1.1). Second, seeking experimental validation of the numerical solution, to determine the accuracy of simulation results (Section 4.1.2) and boundary conditions chosen (Section 4.1.3). However, only few studies in the literature provide models validated against these two aspects: either due to the impossibility of a fine-enough discretization of the study area, given the numerical model used, or due to insufficient experimental data to describe accurately the spatial and temporal scales.

Furthermore, concerning the calculation of thermal comfort indices,

as detailed by Fischereit and Schlünzen (2018), there are two possibilities: either “online” during the simulation or “offline” using back-calculations from model outputs. As an example, an online calculation is considered necessary by the authors only if the heat released by a person impacts the surrounding atmosphere in return, i.e. a bidirectional coupling, in which the passer-by plays an active role, normally seen in indoor modelling. This is because, in the outdoor microclimate, the impact of a person on the thermal environment is small, as the wind speed is usually able to mix the air well; however global simulations with output results with time steps, for example, longer than 20 min, can cause an underestimation of the thermal stress experienced (Fischereit and Schlünzen, 2018). Both inputs and output may have to be even more

frequent to capture microclimate changes if the model is nested (Section 4.3, Fig. 7).

Methodologies and techniques used for validation include remote sensing for city level information (e.g. infrared thermal, visible light, LiDAR and multispectral data), street view images for street level information, and weather monitoring stations for microclimatic and physiological variables, either fixed or mobile, positioned at single or multiple locations (S. Yang et al., 2023). Full-scale pilots in laboratory or in situ have been used, as well as reduced-scale models, and fluid tunnels in the frame of “similitude” types of work (Zhao et al., 2022, 2023). Numerous studies recommend the pursuit of high-resolution flow simulations to refine the description of vegetation and evapotranspiration effects, time-dependent anthropogenic heat fluxes, and thermal interactions with building materials (Zhao et al., 2020). Advancements are needed in the parametrization of urban canopies, seeking model validation from replicable comparisons with high-resolution laboratory and field measurements (Wankhade et al., 2023; Wu et al., 2022; Zhao et al., 2023). Real urban layouts are still required for final validation although the number of studies on real districts is currently limited (Wankhade et al., 2023).

3.1.2. Methodologies and challenges for Substrate-Plant-Atmosphere modelling

The influence of urban green infrastructure on the microclimate arises from aerodynamic effects, solar radiation shading, longwave heat exchange with the environment, and latent and sensible heat flux within the foliage. After Yang et al. (2019) the choice is between CFD and EBM simulation methods. EBM, based on the law of energy conservation for a control volume, cannot provide specific distributions of the determining variables making them suitable for preliminary designs. CFD simulations, on the other hand, are frequently used to describe urban microclimates (Ernst et al., 2022) by coupling velocity, temperature, humidity and pollution fields, resolved at fine scales, at the need of high-resolution information on the urban geometry, relevant specification of boundary conditions, and significant computational resources. Zhu et al. (2023) detailed the methods employed to assess plant geometry, aerodynamic effects and thermal effects, in CFD and EBM.

As detailed by Zhu et al. (2023), in CFD modelling, the more sophisticated methods treat vegetation as a porous medium, adding a momentum source term to the fluid flow equations and incorporating source terms into equations to simulate turbulent interaction with the plant canopy. An alternative method involves adding a pressure loss coefficient to cells occupied by the canopy. Both methods rely on vegetation characteristics such as the mechanical drag coefficient (Cd) and leaf area density (LAD). As for thermal effects, CFD models typically solve the leaf energy balance, accounting for latent heat flux, sensible heat flux, and radiation received by the leaves. The sensible (convective) heat flux is determined by the temperature gradient between leaf surface and the nearby ambient air, across a boundary layer resistance. The determination of latent (phase change) heat flux entails various methods, (i) the volumetric cooling power per unit volume of vegetation (a function of LAD or determined empirically based on the species), (ii) the latent heat flux through leaf stomata (dependent on vapour pressure at the leaf, in the air above the leaf boundary layer, and stomatal resistance), and (iii) empirical methods based on species to estimate evapotranspiration. The radiative heat flux of vegetation considers shortwave radiation absorbed, reflected, and transmitted by vegetation, along with long-wave radiation exchange with the surrounding environment. Shortwave radiation absorption at the canopy level is determined by leaf transmissivity and reflectivity. Calculations are based on LAD and transmission paths, typically using the Beer-Lambert law to assess direct solar radiation flux attenuation. Long-wave radiation exchanges between vegetation and urban settings, as well as solar radiation shading, are typically addressed using the Stefan-Boltzmann law (computationally intensive) or the angle-of-view factor method (also used to calculate the short-wave radiation). The inter-reflections in

urban environments are simulated using ray-tracing models or “radiosity models” or others simplified models.

Zhu et al. (2023) also highlighted that methods employed in EBM simulate sensible heat flux and heat storage, but often overlook latent heat flux. Detailed vegetation models now account for interactions between walls, roads, roofs, and vegetation, in which the temperature of the canopy is determined from the energy balance equation. As regards aerodynamic aspects, vegetation is often treated as a roughness element in drag equations, sometimes by inferring parameter values from simplified CFD modelling. Most EBM also simplify vegetation’s thermal processes, particularly in radiation exchange, treating vegetation as a surface with no depth: energy fluxes occur only from and to the atmosphere, not within the canopy. Recent studies have integrated models of high (stratified) vegetation into EBM to simulate (3D) short- and long-wave radiations between trees, roads, and buildings in street canyons.

Vegetation geometry, for both CFD and EBM, can be treated as (i) a simplified geometry, (ii) a grid model, (iii) a vertically-layered model, (iv) a realistic model, or (v) a planar stretching model (Y. Yang et al., 2019; Zhu et al., 2023). Simplified geometries represent tree canopies as basic shapes like ellipsoids, cylinders, hexahedra, or cones. Grid models divide the spatial volume occupied by the canopy into multiple grids, preserving the plant’s approximate shape throughout spatially-distributed LAD values. The vertically-layered model maintains a constant canopy shape while varying LAD values with height. These methods determine the external profile of the canopy without depicting leaf and branch architecture, characteristics and distribution. Realistic 3D tree shapes can be modelled through precise measurements, although convergence issues may arise in simulations, limiting their application to process-understanding purposes at the elementary scale of individual plants. L-systems, a subset of realistic models, represent plant branching as a structured topology, defining an initial state and applying rule-based transformations (e.g., leaf inclination and LAD) to generate complex fractal patterns resembling natural plants. Stretching models with planar profile projections are often used for urban-scale modelling of vegetation rows, offering a compromise between 2D and 3D modelling.

Again, literature shows a lack of sufficient (or “normalized”) model validation which questions model application for operational purposes (Broadbent et al., 2019; Yang et al., 2019), which is all the more regrettable as multiple positive effects may be obtained from (irrigated) urban vegetation (Zheng et al., 2023). A clear perspective mentioned is verifying the effects of different types of urban vegetation, whether isolated or combined, and evaluating model performance across different seasons and meteorological conditions (Tsoka et al., 2018).

3.2. Review of numerical models

Many models reviewed exhibit specific characteristics in link with initial demands or development objectives, before adaptations to incorporate new elements of the urban environment, or refinements to enhance existing features. None has been developed on purpose to assess microclimatic effects drawn from the irrigation of urban vegetation, but all needed components seem to separately exist. Fig. 4 summarizes model functionalities and capabilities in four main areas: general information, physical modelling, applications, and output variables. Emphasis is placed on the possibilities offered for spatial and temporal discretization, as required to correctly quantify the spatial and temporal dynamics of the microclimatic effects, governing those of thermal comfort indices, for different urban configurations and management strategies. Additionally, the indicative duration of a simulation is considered a rough proxy of the computational power required, and of the time needed for getting to grip with the model. The typical temporal (whether for annual, seasonal, daily, or hourly studies) and spatial scales of application are also provided. The physical modelling entries aim to identify the methods used to describe aerodynamic and radiative processes in the study area, as well as the effects of vegetation. Much

			<table border="1"> <tr> <th colspan="2">Legend</th> <th>&</th> <th>CFD</th> </tr> <tr> <td>✓</td> <td>Yes</td> <td>&</td> <td>EBM</td> </tr> <tr> <td>○</td> <td>No</td> <td>‡</td> <td>Data-driven</td> </tr> <tr> <td>○</td> <td>Possible</td> <td>‡</td> <td>Coupled</td> </tr> </table>																						Legend		&	CFD	✓	Yes	&	EBM	○	No	‡	Data-driven	○	Possible	‡	Coupled
Legend		&	CFD																																					
✓	Yes	&	EBM																																					
○	No	‡	Data-driven																																					
○	Possible	‡	Coupled																																					
			Envi-met	RayMan*	ANSYS Fluent*	OpenFOAM*	Solveig*	TEB	Ladybug Tools*	PALM-4U	SkyHelios	MMRT	VTUF-3D	UT&C	PHOENICS	Solene microclimat*	CitysimPro	UGBE	Cradle acSTREAM	PUCM	3D-USM	Green CTC	STAR-CCM+	BEP-Tree																
General information	Classification	Model type	&	§	&	&	§	‡	&	§	§	§	§	&	‡	§	§	§	§	§	§	&	§	§																
	Availability	Free access (Free)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓															
		On demand (Restricted)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓															
		Paid license	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓															
	Environment	Windows	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓															
		Linux	✓	✓	✓	✓	✓	✓	✓	○	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓															
	Duration of simulation*	Fast (Min. ≤ Duration ≤ Hours)	✓	✓	✓	✓	✓	✓	○	✓	✓	✓	✓	✓	✓	✓	○	✓	✓	✓	✓	✓	✓	✓	✓															
Slow (Hours ≤ Duration ≤ Days)		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
Update	Recent (≥ 2019)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
	Old (< 2019)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
Time discretisation	Time range ≤ Minutes	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	○	✓	✓	✓	✓	✓	✓	✓	✓	✓																
	Time range ≥ Hours	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
2D Spatial discretisation	Spatial range < 1 m	○	✓	✓	✓	✓	✓	○	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
	Spatial range ≥ 1 m	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
Physical modellings	Aerodynamics	CFD	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
		Coupled with CFD Software	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○															
	Simple model	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
Radiation	Radiosity	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
	RayTracing	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
	Others	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
Vegetation Effect	Shadow	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
	Porosity	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
	Evapotranspiration	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
	Irrigation	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○																
Applications	Time scale	Annual (Simulated period ≤ Year)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
		Daily (1 or a few days)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
	Spatial scale	Canyon	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓															
Neighborhood		○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○																
Use	Thermal comfort (C)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
	Energy need (B)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
Outputs	Thermal comfort variables	Ta and RH	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
		Tmrt	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																
		WIND speed	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓															
		UTCI or PET	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓															
		Other Thermal COMFORT index	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○															

Fig. 4. Summary of general information (including model types, see Fig. 3), Physical Modelling, Applications and Outputs of the 22 numerical models identified in this literature review. Cells are ticked with labels “Yes” (widely applied in literature/practice), “Possible” (theoretically feasible but with few or no examples in the literature), or “No” (not provided by the software). Thermal comfort variables are air temperature (Ta), relative humidity (RH), mean radiant temperature (Tmrt), wind speed, Universal Thermal Climate Index (UTCI), Physiological Equivalent Temperature (PET) and others. Models marked with (*) are detailed in the next sections. Table adapted from Muanda (2024).

attention is drawn to the latter, checking which models are able to account for shadow occurrence (interception of solar radiation by vegetation), porosity (altered airflow due to vegetation), evapotranspiration effects (such as air humidity gain, energy dissipation and/or surface temperature changes), and variations in irrigation regimes (affecting soil properties, evapotranspiration intensity and/or supporting urban water management).

Due to a patent lack of information, Fig. 4 cannot report on validation issues, while validation clearly is a crucial, non-trivial procedure for the complex modelling objectives assigned here. Some authors note that less than half of the studies are validated against experimental data (Dey and Joshi, 2023; Toparlar et al., 2017) which is strikingly low, as validation is required as soon as more than one climatic factor (e.g., air temperature, relative humidity, wind speed, or mean radiant temperature) is modelled (Dey and Joshi, 2023). Furthermore, most studies did not validate all climatic variables taking part in the calculation of thermal comfort indices (e.g., PET and UTCI). This is either due to the lack of measurement device, or know-how due to the complexity of the variable analyzed (e.g. Tmrt), or to the fact that the constitutive variables of those indices do not explicitly appear among model variables. This comes at the risk of (silenced) low correlation between simulation results and observational data, with errors possibly arising from discrepancies between the real study site and the computerised site, among other factors (Lam et al., 2021). Still some studies have taken in-situ measurements of climatic factors but those are limited to only a few discrete locations providing a likely too sparse array of data (Dey and Joshi, 2023). Precisely, such data collection may be enough to assess

model performance in terms of magnitude of the signals, while inappropriate for validating transient heat transfers. Finally, the link between microclimatic data and models still needs to be fully explored, both in terms of minimum data requirements and discretization, and as regards the associated “mandatory” model features and components, to feed with those data. This is a pending question with high methodological stakes.

Fig. 4 does not explicitly address the irrigation topic either. Irrigation has indeed not yet been modelled as a lever of action on evapotranspiration, thus as a partial control to regulate local microclimatic conditions and thermal comfort, when deciding urban water management. However, some of the models that incorporate the principle of “infinite urban canyon parameterisation”, such as TEB (de Munck et al., 2013) or UT&C (Meili et al., 2020), include sub-models to handle the water balance of the whole system. Those consider the impact of different soil moisture conditions, linked to irrigation inputs, but their aim is to provide average characteristics at the neighbourhood scale, above the scales of interest here.

Similarly, ENVI-met incorporates irrigation through a coefficient that adjusts soil moisture levels thus dictates the response to the climatic demand (Wollschläger et al., 2022) but model discretization is too coarse to provide street-scale answers. Furthermore, SOLENE-microclimat (Azam et al., 2018; Robineau et al., 2022), provides a thermal model of pavement irrigation but does not include any explicit soil or hydrological model: water stress is only indirectly accounted for, via parameterisation of the evaporation rate. Nevertheless, SOLENE-microclimat has been coupled with the MARIE hydrological model,

which estimates actual evapotranspiration from local climate inputs for urban green areas ranging from a few square metres to several thousand (Robineau et al., 2022). MARIE accounts for both low (shrubs, grass, perennial plants) and high (trees) vegetation strata, enabling assessments of urban greenery effects on evapotranspiration and air temperature at the district scale. However, this scale extends beyond the present study's scope.

Based on existing microclimate model classifications (Fig. 2), the seven most cited models, representing distinct categories and marked with (*) in Fig. 4, were selected for detailed analysis (Tables 3 and 4). These tables provide a direct comparison of the key features of each model, including model type, general overview, domain, mesh and temporal resolution, approaches to vegetation representation, and strengths and weaknesses.

Regarding the coupling potential of these models with other numerical tools, ENVI-met is sometimes integrated with models such as Weather Research and Forecasting (WRF) for atmospheric inputs (McRae et al., 2020) or with BES models like EnergyPlus and TRNSYS (Palme and Salvati, 2021; Salvati et al., 2022). No strong direct coupling was found for RayMan in the reviewed literature. ANSYS Fluent has been coupled with mesoscale models (WRF, Wang and Li, 2016), BES models like EnergyPlus (Fallahpour et al., 2022), and plugins such as Ladybug and Honeybee (Fallahpour et al., 2022). OpenFOAM is commonly integrated with BES models (e.g., EnergyPlus, Miguel et al., 2021), mesoscale models (e.g., WRF, Wong et al., 2021), and wind-driven rain simulations (WDR, Kubilay et al., 2018), as well as platforms like Ladybug Tool and Grasshopper (Gholami et al., 2022). As part of UMEP, SOLWEIG is linked with other models in the platform, such as Urock, which employs a simplified parametric model for airflow calculations (Bernard et al., 2023). Ladybug Tools, a suite of open-source environmental analysis plugins (Sadeghipour Roudsari et al., 2013), is inherently based on model coupling. No reported couplings were found for SOLENE-microclimat within the reviewed WOS literature. However, before being coupled with code_saturne (Malys et al., 2015), its predecessor, SOLENE, was integrated with the CFD models N3S (Vinet, 2000) and ANSYS Fluent (Bouyer, 2009), as well as the building energy model BuildSysPro (Merlier et al., 2019).

As detailed by Lauzet et al. (2019), the trend towards interoperable models is promising, as it enables a multi-scale assessment of urban impacts, potentially leading to more realistic simulations. However, significant challenges remain, including the heterogeneous architecture of numerical models and discrepancies in spatial and temporal scales. These factors can limit compatibility or necessitate simplifications or interpolations that may reduce the accuracy of the analysis.

4. Discussion and perspectives

4.1. Validation of the numerical models

To ensure the reliability and applicability of numerical models in urban microclimate studies, a structured validation framework may be proposed, composed of three complementary levels: (i) numerical verification (Section 4.1.1), to assess discretisation quality and mesh independence; (ii) physical validation (Section 4.1.2), to evaluate whether key physical processes and outputs are accurately reproduced against in situ measurements or credible reference data; and (iii) boundary condition assessment (Section 4.1.3), to examine the representativeness and accuracy of the input climatic and urban morphological data used as boundary conditions. Depending on the level of complexity of the model, full validation may not always be feasible. However, targeted verification procedures (on the key variables) can provide sufficient confidence for models with a strong physical rationale. This tripartite approach is used here to review the validation efforts and needs of the main models considered (Fig. 5).

4.1.1. Numerical verification

Based on Figs. 2, 3 and 4, and on the arguments developed in Sections 2 and 3, a transverse view on models types and features shows a specificity of the most sophisticated CFD models (ANSYS Fluent, some specifications of OpenFOAM). Only such models can make sure the results are independent from the chosen discretization and mesh, thus demonstrate the consistency of the approach and arguably assume its reliability. Of course, definitive proof should be obtained by confrontation with in-situ experimental data, while establishing the exportability or genericity of the approach would be even more demanding. By contrast, simpler approaches would either necessitate partial cross-validations with refined models (where discretization is questionably coarse) or at least a discussion on their "terms of use" and irreducible, intrinsic uncertainties, fully mentioning the trade-off between simplicity and accuracy. This would better inform on their relevance and possible operational use in the selected contexts for which they have been tuned. However, as previously recalled and frequent in modelling, a good understanding of the physical processes at play, combined with a bundle of indirect evidence, will often be enough to rightfully claim the modelling approach is sound, if not precise enough.

For example, ENVI-met, due to its architecture, does not always meet the good practices: mesh independence is sometimes not achieved because the minimum grid size available is not sufficient (Crank et al., 2018). For the other models (RayMan, SOLWEIG, SOLENE-microclimat and Ladybug tools), it seems that no studies have provided strong-enough verification procedures.

4.1.2. Physical validation

Another crucial validation is that of model variables associated with the determining physical processes, starting with those in link with radiation. Radiative exchanges indeed play a significant role in the energy balance that dictates surface temperature values, hence Tmrt, always with a strong influence on thermal comfort (Kántor and Unger, 2011; Lindberg et al., 2008). Here again, very few models discuss validation issues for their radiative part. On the contrary, several authors have suggested validating only air temperature and relative humidity, discarding wind speed and Tmrt (Lam et al., 2021; Tsoka et al., 2018). This is surprising as a mere validation of air temperature and relative humidity will likely not guarantee the reliability of the calculated comfort indices, drawn from multiple interacting variables (see the calculation scheme in Fig. 7).

Another issue is that as ENVI-met, SOLWEIG, and RayMan have been the subject of ancient validation works, including on Tmrt (Crank et al., 2020; Du et al., 2021; Gal and Kántor, 2020; Kántor et al., 2018; Tsoka et al., 2018), that have not been renewed for the latest model versions. For SOLENE-microclimat, validation has been carried out for surface temperatures and other radiative aspects, but neither for Tmrt nor for the other variables of thermal comfort (Palme and Salvati, 2021).

There is thus a significant need to establish and promote a common validation method, which should encompass the several variables involved in the calculation of thermal comfort indices, as suggested in the benchmarking approach for urban microclimate models by Gresse et al. (2024, 2025). The stake is high, as thermal comfort values will be claimed by modellers and urbanists, in direct link with societal concerns and water management policies. As regards water use efficiency and justifications, the additional cooling effects sought from irrigation of the urban vegetation (the chain of δ terms in the calculation scheme in Fig. 6) should be evaluated by comparison with a reference case without irrigation, either real (measurements available) or fictitious (simulated by a validated model). Finally, validation strategies could likely rely on what is known from the sensitivity of thermal comfort indices to their constitutive variables, in the expected ranges of values, to indicate where to put the modelling or measurement effort. In this view and logic, the Tmrt appears altogether crucial and very difficult to calculate. Fortunately, in situ evaluations with low-cost and easy-to-implement techniques (Grosdemouge, 2020) seem feasible and are currently

Table 3

Comparison of different microclimate models, highlighting model type, name, general overview, mesh, domain and temporal resolution, vegetation integration, as well as strengths and limitations of each model. Key references for the information presented include the authors' experience as users of the software, along with ENVI-met (Bruse, n.d.; Gal and Kántor, 2020; Rosso et al., 2018; Salata et al., 2016; Yin et al., 2019), RayMan (Matzarakis et al., 2015; Palme and Salvati, 2021), ANSYS Fluent (ANSYS, Inc., 2023; Brozovsky et al., 2021; Defraeye et al., 2014; Liu et al., 2022; Zhang et al., 2023) and OpenFOAM (Green Shields, 2023; Kubilay, n.d.; Kubilay et al., 2018; Teichmann et al., 2021).

Microclimate model		General overview	Mesh, domain and temporal resolution	Vegetation	Strengths	Weaknesses
Type	Name					
CFD	ENVI-met	<ul style="list-style-type: none"> → Commercial 3D software designed to simulate the microclimates complex interactions between the materials and shapes of urban surfaces, vegetation and atmosphere. → Various methods for forcing boundary conditions, from the full forcing of all climate variables (usually ranging between less than 30 min and 1 h) to a simplified version that only includes air temperature and relative humidity (less accurate). 	<ul style="list-style-type: none"> → Cubic grid, with spatial resolutions (grid size) ranging from 0.5 to 10 m. Grid size is usually greater than or equal to 1 m due to potential model instability. → The temporal resolution of ENVI-met ranges from 1 to 5 s, for simulations lasting from a few hours to several days. 	<ul style="list-style-type: none"> → Vegetation is modelled as clusters cells with root density in the soil model and Leaf Area Density (LAD) in the atmospheric model, enabling soil water dynamics and evapotranspiration estimation. → Aerodynamic effects are included via source terms in the RANS equations, based on LAD. → Heat and moisture fluxes at leaf surfaces influence air temperature and humidity, with radiation interactions reducing energy flux to urban surfaces through a coefficient dependent on LAI and sky visibility, modelled via an L-systems approach. 	<ul style="list-style-type: none"> → User-friendly environment, ease of use with a clear manual and modelling architecture aimed at studying the impact of vegetation on the urban microclimate, with online output data of Tmrt and different bioclimatological indices (such as PET, UTCI). → Covering a wide range of potential applications due to the various variables it can calculate. → Highest number of studies among the evaluated tools, providing a broad data foundation for performance assessment. → Constantly evolving and updating tools. 	<ul style="list-style-type: none"> → Limited flexibility in configuring the physics of the model, restricting its adaptability for specific case studies and complex multiphysics settings. → Pre-established turbulence model: RANS equations with a 1.5-order E-ε closure → Cubic grid may lead to errors in calculating shading rates and drop shadows (tendency to wash away the differences in radiation amounts within the domain) → For small study domains like an urban canyon, the tool's spatial and temporal scale affects results, making them dependent on these factors and highlighting its limitations at this scale.
		EBM	RayMan	<ul style="list-style-type: none"> → Open source 1D diagnostic model designed to perform solar and thermal radiation calculations. → Calculate the sky view factor from hemispherical images or "obstacle files" built from the surrounding urban morphology, in vector-based ASCII format (created manually or imported from geospatial data using "Shp to Obs" a QGIS plugin). 	<ul style="list-style-type: none"> → No mesh, represents a single point in space. → Results independent of time. 	<ul style="list-style-type: none"> → Only the shading effect of trees is considered. → Trees are defined in obstacle files by specifying their type (conifer or deciduous), position, height, crown radius, trunk height, trunk diameter, albedo, and emissivity → Simulate the shadows cast by trees, thus their impact on some of the variables of the local microclimate and thermal comfort index.
CFD	ANSYS Fluent			<ul style="list-style-type: none"> → Commercial fluid simulation software (2D or 3D) with advanced physics modelling capabilities. → Offers several radiation, aerodynamics and thermal models commonly employed in urban microclimate studies, allowing models with varying degrees of complexity to be configured or combined depending on the purpose of the study. 	<ul style="list-style-type: none"> → Supports advanced mesh configuration, mainly hexahedral and poly-hexcore. → Wide range of mesh sizes, with the finest mesh reaching 4×10^{-6} m (e.g., a leaf) and up to 0.15 m for larger domains (e.g., a campus). → Temporal resolution depends on mesh and domain physics; improper settings prevent convergence. 	<ul style="list-style-type: none"> → The impact of vegetation on the microclimate depends on user-defined domain settings, allowing various representation levels from geometry to physics and surface properties. → Examples: Vegetation can be modelled as porous media with source terms in RANS equations, using ray tracing for shading, or as semi-transparent canopies accounting for radiation interactions. Green walls include turbulence and cooling power terms, while grass evapotranspiration follows the Penman-Monteith equation.
		CFD	OpenFOAM	<ul style="list-style-type: none"> → Open source fluid simulation software (2D or 3D) with advanced physics modelling capabilities. 	<ul style="list-style-type: none"> → Supports advanced mesh configuration, mainly hexahedral and polyhedral. → Wide range of mesh 	<ul style="list-style-type: none"> → The impact of vegetation on the microclimate depends on user-defined domain settings, allowing various representation levels from geometry to physics and surface

(continued on next page)

Table 3 (continued)

Microclimate model		General overview	Mesh, domain and temporal resolution	Vegetation	Strengths	Weaknesses
Type	Name					
		→ Offers several radiation, aerodynamics and thermal models commonly employed in urban microclimate studies, allowing models with varying degrees of complexity to be configured or combined depending on the purpose of the study.	sizes, with the finest mesh reaching 10^{-4} m (e.g., isolated building) and up to 0.4 m for larger domains (e.g., street canyon). → Temporal resolution depends on mesh and domain physics; improper settings prevent convergence.	properties. →Its accessibility and architecture allow for the development of modules (e.g. urbanMicroclimateFoam) or solvers (e.g. UhiSolver) developed specifically to describe the effects of urban vegetation on the urban microclimate that can be used by the tools' user community.	utilised and improved by other users. →Powerful multiphysics modelling tool, providing highly accurate results. →Setting up and calibrating the tool according to the needs of the project and the level of information available in the study domain. →Temporal and spatial scale according to the need to represent the urban microclimate and thermal comfort indices. →Constantly evolving and updating tools.	solvers and modules. →User needs to have in-depth knowledge of the physical processes involved in the study. →Computational resources and time to conduct the modelling are significant and sometimes make the study unfeasible. →Sufficiently fine experimental data to validate the model.

evaluated, prior to their inclusion in operational validation procedures. However, when the study context allows it, proper validation requires the use of more accurate methods for calculating T_{mrt} , such as the six-direction radiometer method, in order to overcome the limitations of methods like the black and grey globe thermometers (Grosdemouge, 2020; Kántor and Unger, 2011).

4.1.3. Boundary conditions assessment

Most climatic data come from weather stations outside the domain, which introduces uncertainties in air temperature and relative humidity, radiation, and likely even more in wind speed and direction (Aliabadi and McLeod, 2023; Gal and Kántor, 2020). Correction models such as UWG to assess in-situ values (Bueno et al., 2013) also suffer limitations, as resorting to descriptors (urban morphology, land use, meteorological conditions) either inaccurate or uncertain themselves, especially in very heterogeneous urban areas (Gunawardena and Steemers, 2019; Salvati et al., 2016; Xu et al., 2022). Furthermore, while UWG has been updated to improve radiation, vegetation, and heat transfer calculations, it may still not fully capture all the determining physical processes (Aliabadi and McLeod, 2023).

In addition, it is important to consider that certain weather stations do not measure all the radiative parameters required as inputs for the models. For instance, longwave incoming radiation is often not measured, and in the case of shortwave solar radiation, the distinction between its direct and diffuse components—required by certain models—is frequently unavailable. It is common practice to use approximated methods from the literature to estimate these components, since such measurements are not systematically recorded at weather stations. However, these simplifications may introduce biases into the model and potentially affect validation outcomes (Gal and Kántor, 2020; Muanda, 2024; Wallenberg et al., 2023). However, correction alternatives have not yet been proposed in the literature and remain scarcely studied, particularly with regard to their impact on model outputs.

This is even more problematic for wind velocity values and profiles, often very different between connected streets or close neighborhoods. Most CFD models commonly use power or logarithmic laws to retrieve wind profiles from (horizontal) wind values measured at 10 m. However, such laws have not been designed for urban contexts thus may be used outside their conditions of validity. An alternative is downscaling large-scale simulation models (McRae et al., 2020) to the specific area of interest, at high computational costs.

However, remedies may also be sought in the same pragmatic logic as for the determining physical processes and variables, seeking precision and validation in priority for the boundary conditions expected to be crucial. Those are, a priori, these known to control the variables to

which thermal comfort indices are the most sensitive, in a given context. Here again, physical sense will spare some effort. In numerical ways, it could rely on the dimensionless formulation of the system of equations, as only mentioned here and there in the literature (Mballo et al., 2021). This would help identify the key dimensionless groups and parameters, and also the associated physical parameters to be determined (fitted, measured) whatever the level of details required by the model. Finally, the most explicit and sophisticated models will need to retrieve or work with exact boundary conditions (e.g. the specific heat of concrete and that of a canopy have different values, placed in the urban scene) while simpler models will work with effective or apparent boundary conditions (e.g. a lumped specific heat value for a composite object whose exact location is not required).

The urban morphology used for model validation has a strong influence on the quality of the validation. The more complex the environment, the harder it becomes to identify the potential sources that may have affected the results, due to the intricacy of the urban scene (Crank et al., 2020; Ouyang et al., 2022). For robust validation, the spatial scale must be taken into account. When possible, validation should be conducted at multiple scales (Fig. 6): starting with simple surfaces, followed by urban canyon configurations, and ultimately progressing to real, complex urban environments (Muanda, 2024; Musy et al., 2023).

Simple surfaces, minimally affected by multiple urban objects, allow for the validation of key parameters such as temperature and energy fluxes (Azam et al., 2018). The urban canyon scale offers an intermediate step, incorporating essential components like buildings, ground, and vegetation (Garcia De Cezar et al., 2024; Mballo et al., 2021). Finally, real urban environments provide an opportunity to test the model under highly complex conditions involving multiple interactions between buildings, materials, and microclimatic factors (Gal and Kántor, 2020; Wallenberg et al., 2023). These three validation scales are complementary and should be further explored to assess the model across different levels of urban complexity.

4.2. Impact of irrigated vegetation

There is a clear and recognized gap in literature, lacking models and experiments specifically built to study the role played by urban vegetation under different irrigation regimes, in potentially and partly regulating the local microclimate (Antoszewski et al., 2020; Tsoka et al., 2018; Yang et al., 2019). Although this review mentions multiple approaches and models that could be adapted or tuned for the indicated purposes, these are more or less good starting points, not achieved and fully available material. Future works should in particular explore the

Table 4

Comparison of different microclimate models, highlighting model type, name, general overview, mesh, domain and temporal resolution, vegetation integration, as well as strengths and limitations of each model. Key references for the information presented include the authors' experience as users of the software, along with SOLWEIG (Aminipouri et al., 2019; Lindberg et al., 2008, 2018; Robinson and Stone, 2004), Ladybug Tools (Camporeale and Mercader-Moyano, 2023; Evola et al., 2020; Kamel, 2021; Sadeghipour Roudsari et al., 2013) and SOLENE-microclimat (Miguet, 2000; Miguet and Groleau, 2002; Musy et al., 2021).

Microclimate model		General overview	Mesh, domain and temporal resolution	Vegetation	Strengths	Weaknesses
Type	Name					
EBM	SOLWEIG	<p>→Open source 2.5D model that uses 2D GIS information (x, y) with an added limited third dimension (z) to simulate the depth of the objects located in urban scenes (buildings, trees).</p> <p>→It is integrated into UMEP, a plugin for QGIS.</p> <p>→It is a purely radiative model that focuses on the balance of radiative fluxes.</p> <p>→Longwave radiations are handled with the simplified radiosity algorithm relying on an anisotropic sky model.</p> <p>→Primarily used for microclimatic applications, at the neighbourhood scale.</p>	<p>→No limits in mesh size, with studies reaching a few centimeters.</p> <p>→Mostly used with a 1 m resolution for its output variables, in line with the resolution of its geometric inputs, which must have the same resolution.</p> <p>→The lowest resolution found was 0.3 × 0.3 m obtained from LiDAR data.</p> <p>→The temporal resolution has no limit, ranging from a few seconds to an hour, depending on the climate input file.</p>	<p>→Accounts for the shape of vegetation (diameter, tree height, trunk height) using a digital surface model and an average tree transmissivity, based on the "apparent" LAD value averaged over the whole domain.</p> <p>→Only considers the shading effect of trees on radiation, not on evapotranspiration, but the SUEWS model (another UMEP sub-model) can be used to account for latent heat flux, and subsequently introduce the effect of vegetation on air temperature and humidity.</p>	<p>→ User-friendly environment, as a QGIS plugin, it benefits from an environment familiar to many urban planners.</p> <p>→Low computational cost, to simulate large domains in a few minutes, for simulation horizons of usually a few hours.</p> <p>→In certain circumstances, SOLWEIG could also give similar results as more complex models such as ENVI-met.</p> <p>→Online output data of Tmrt.</p> <p>→Requires low level of understanding of the physical processes to be simulated.</p> <p>→Constantly evolving and updating tools.</p>	<p>→ Limited flexibility in configuring the physics of the model, restricting its adaptability for specific case studies and complex multiphysics settings.</p> <p>→ Lack of embedded evapotranspiration modelling.</p> <p>→ Likely oversimplified calculation of surface temperatures.</p> <p>→ Due to the spatial and temporal resolution being defined according to the type of input data, it has a limitation of representing temporal and spatial scale according to the need to represent the urban microclimate and thermal comfort indices.</p> <p>→ It does not model airflows that can be critical for modelling the urban microclimate.</p>
		Data-driven	Ladybug Tools	<p>→Open-source plug-in collection for environmental simulation, mainly in Grasshopper.</p> <p>→Ladybug: Imports climate data, visualises environmental variables, and analyses microclimate.</p> <p>→Honeybee: Integrates Radiance, OpenStudio, and EnergyPlus for daylighting, energy, and thermal comfort analysis.</p> <p>→Dragonfly: Enables district-scale modelling with URBANopt SDK and UWG for urban form and comfort studies.</p> <p>→Butterfly: Uses OpenFOAM for CFD simulations of wind patterns and indoor airflow.</p>	<p>→Few details were available on the dimensions of the study domain, mesh size and simulation time step.</p> <p>→A case study indicates the use of a 3 × 3 m mesh to simulate an urban sector.</p> <p>→Two studies indicate hourly time scales for UTCI and Tmrt.</p>	<p>→Ladybug and Honeybee plugins are limited in their ability to accurately measure the cooling effects attributable to evapotranspiration process within green spaces: they primarily focus on assessing the shading effects of buildings on pathways between obstacles.</p> <p>→Alternative proposals are to use the UWG within Ladybug Tools to account for vegetation evapotranspiration: specifically, the UWG models vegetation evapotranspiration (and express sensible heat as a latent fraction) without performing a full moisture balance to represent the impacts on relative humidity.</p> <p>→Although the use of the UWG provides some insights, its results should be interpreted with caution.</p>
Coupled	SOLENE-microclimat	<p>→Simulates urban interactions, at various scales (building, street, neighbourhood) with a fine spatial resolution.</p> <p>→Its rationale is a thermo-radiative model that calculates radiative exchanges, using the radiosity method.</p> <p>→Account for aerodynamic exchanges, the thermo-radiative model is coupled with "code_saturne", a CFD model based on the RANS equations with a k-ε closure.</p>	<p>→Triangular mesh, which can be as fine as a few centimeters.</p> <p>→Mesh size is not systematically reported in the literature.</p> <p>→Time scales can be shorter than minutes, but usually hourly is used.</p>	<p>→Accounts for the evapotranspiration of trees, vegetated facades and rooftops.</p> <p>→Trees are modelled as radiative surfaces and volumes with an impact on aerodynamics, and assigned properties of transmission, reflection and absorption, thus shading.</p> <p>→The CFD model treats each tree cell as a mixed volume of air and foliage, with a specific aerodynamic resistance and a single mean temperature.</p> <p>→The energy balance for these cells includes radiative fluxes and latent and convective energy exchanges, applicable only to cells adjacent to the tree's external surface.</p>	<p>→ Covering a wide range of potential applications due to the various variables it can calculate: analysis of local climate, energy performance, indoor and outdoor thermal comfort.</p> <p>→Online output data of Tmrt.</p> <p>→Simulation environment that allows using the functionality of different open source software.</p> <p>→Constantly evolving and updating tools.</p>	<p>→ Limited flexibility in configuring the physics of the model, restricting its adaptability for specific case studies and complex multiphysics settings.</p> <p>→ Few documents available to understand the physical models integrated into the models.</p> <p>→ The vegetation models for trees and green roofs have not yet been validated (non-physical surface temperature).</p> <p>→ User needs to have in-depth knowledge of the physical processes involved in the study.</p> <p>→Computational resources and time to conduct the modelling are significant and sometimes make the study unfeasible.</p>

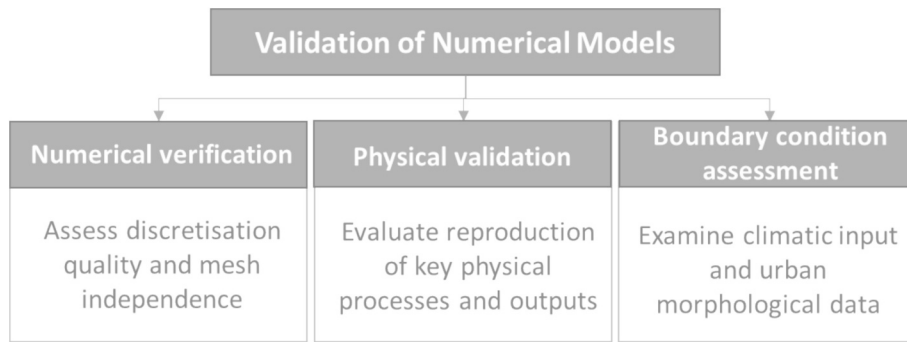


Fig. 5. Simplified framework for the validation of numerical models.

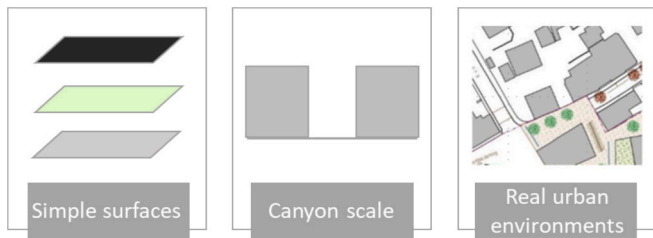


Fig. 6. Different complexities of study domains, which allow for different validation procedures.

effects of different plant types, physiological characteristics, and planting arrangements on the urban microclimate, especially for their effects on shading, evapotranspiration, surface leaf temperature, and as regards their response to irrigation (Fu et al., 2022). The local microclimatic effects of combined trees and other vegetation types should be

addressed, as such combinations seem promising in acting upon all the constitutive variables of thermal comfort indices. Moreover, diverse growth and irrigation strategies should be considered, exploring their ability to enhance evapotranspiration fluxes (Fig. 7) and even the opportunity of different irrigation piloting strategies during heatwaves or standard periods (Garcia De Cezar et al., 2024; Kubilay et al., 2023).

In a wider perspective, studying plant combinations should also lead to studying different arrangements and vegetation layouts, at different connected and embedded scales, so as to think the issue in terms of green (and blue) grids, in certain streets and across the city (Fu et al., 2022). This also includes understanding the extent and duration of irrigation effects (in blue in Fig. 7) which in turn helps determining the preferable vegetation types, for different urban zones, and the most appropriate irrigation methods based on local water availability. In regions where irrigation does not significantly enhance temperature mitigation, plants with good green cover and low water demand should be prioritised to conserve the city's water resources. Conversely, in cities where regulating plant evapotranspiration through irrigation is essential, strategies

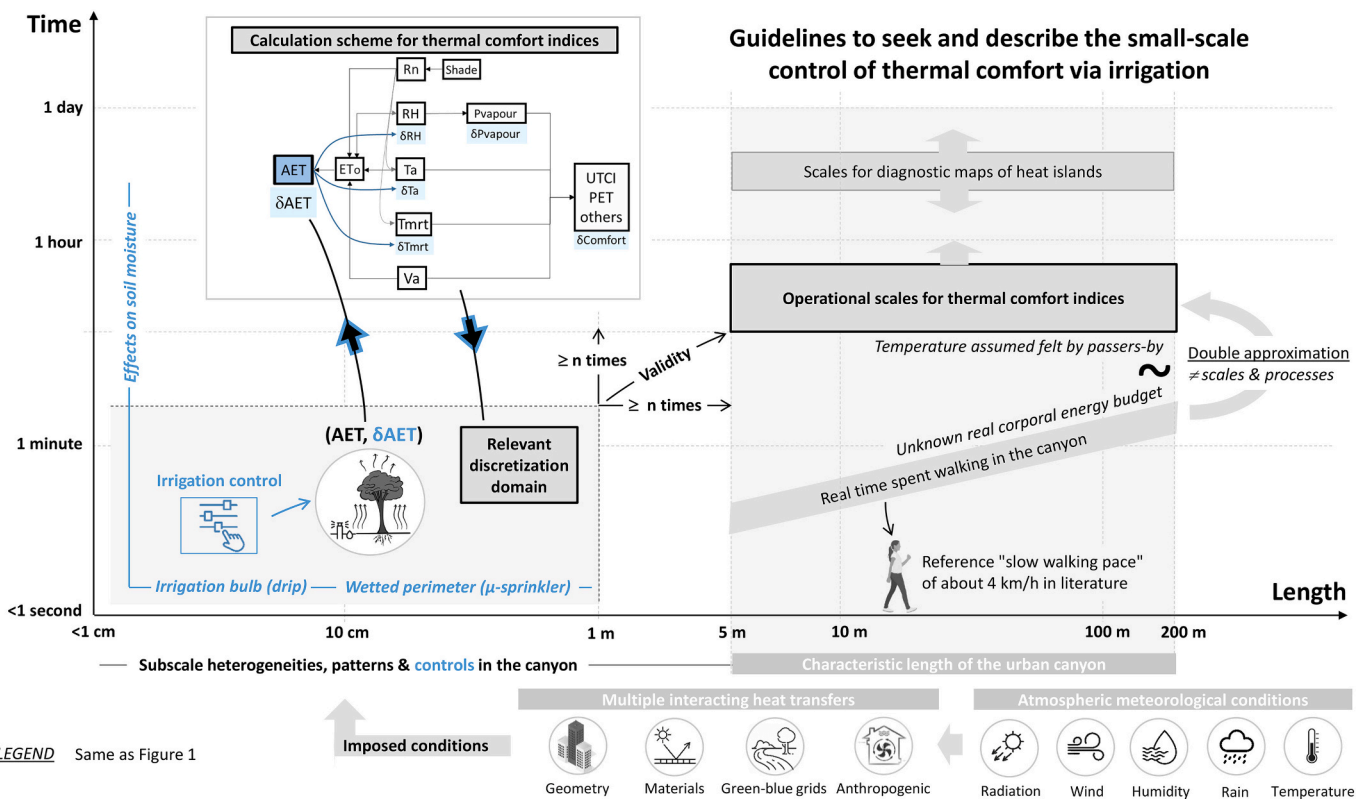


Fig. 7. Guidelines to seek and describe the street-scale controls of thermal comfort via irrigation, seen as a lever of action among multiple other interacting factors. A fine-enough discretization (n times) of all determining physical variables is required to ensure validity of the approach and allow operational applications.

such as rainwater harvesting or the use of recycled water should be considered.

Concrete recommendations for adapting existing numerical models to incorporate irrigation as a control variable focus on the role of irrigation in increasing soil moisture availability, which directly influences the ability of the soil-plant system to produce evapotranspiration. This process is governed by several interacting factors, including solar radiation levels, specie-specific physiological traits, and soil properties (Cheung et al., 2022b). The resulting effects on the local microclimate—modulated by environmental conditions and plant needs—include enhanced evapotranspiration (raising ambient humidity), reduced surface temperatures, and increased solar radiation interception due to canopy shading (Cheung et al., 2022a).

To more effectively represent irrigation in existing modelling frameworks (Section 3.1.2), we propose several practical strategies: (i) enhancing soil and vegetation modules to integrate dynamic soil moisture inputs, either via user-defined irrigation schedules or coupling with hydrological models (de Munck et al., 2013; Robineau et al., 2022); (ii) refining boundary conditions related to latent heat exchange and plant responses to water availability (Wollschläger et al., 2022); (iii) incorporating plant-specific traits such as stomatal conductance and in particular water stress thresholds in regulating transpiration (Meili et al., 2020); and (iv) validating model performance against observational datasets that distinguish between irrigated and non-irrigated scenarios. Implementing these improvements would support accurate simulations of irrigated vegetation and contribute to informed, water-sensitive urban planning and provide guidelines to model selection.

4.3. Guidelines for model selection

In the development of urban planning projects, various actors, tools, scales of operation, and action levers may be identified. The actors include:

- the public sector: responsible for executing works and establishing legislative guidelines for current and future urban planning according to needs;
- entrepreneurs: private sector entities that undertake and invest in urban works and specific areas of interest;
- consulting firms: which establish and assist in the design of urban works;
- and citizens: who reside and live in the urban environment.

Additionally, researchers (who identify and deepen societal knowledge related to the urban ecosystem) are indirectly involved, all the more as when socio-technical objects are manipulated, which is the case here. Available tools for urban planning decision-making include various types of numerical models (such as those studied in this article), theoretical bases (physics, mathematics, agronomy), regulations (stipulated by the public sector), and the accumulated experience of the actors. The scales of operation, where different action levers can be applied to achieve urban thermal regulation, range from individual buildings (e.g., hospitals, schools) to streets, blocks, or entire cities. Those action levers involve identifying sensitive zones (hotspots) at the identified scales of interest, as well as evaluating different strategies for creating cool islands for both current scenarios and their performance in future climatic conditions.

In this diverse decision-making context for urban thermoregulation, it is emphasised that all tools are important and necessary as they are complementary. However, when choosing numerical models for different urban design studies, users face many questions about which model is the “best.” Primarily, the magnitude of the phenomena to be represented in thermal comfort studies at the pedestrian scale, as detailed in Fig. 7, should be considered.

Due to the complexity of the urban scenes, and that of the scenarios of interest, obtaining reliable results with appropriate spatial and

temporal propagation of thermal effects requires equally complex models that explicitly represent the area’s physics. Currently, only the most sophisticated CFD models can provide the necessary level of detail, but their use entails challenges related to operational complexity, simulation time, and high computational costs. This study highlights various numerical models, each with their strengths and weaknesses, for addressing these issues. The main factors guiding the selection of the most appropriate numerical model include the type of study (scenario comparison, absolute attenuation value, sensitive zone identification, effects on future climate, and analysis period), physical aspects to be considered, project timeline, available software and computational capacity, and information about the study area.

Fig. 8 summarizes and critically exemplifies the functionalities of 22 selected numerical models, clustering them by similar characteristics and positioning them according to their complexity level (user manipulation and required simulation time) and typical study type. The graph also underscores the need to develop less robust, more user-accessible models that enable faster simulations with finer spatial discretisation. Thus, there is a gap between research (high complex models) and the operational field (low and medium complex model) because although some models are advanced in research area, those who have to use them in urban development projects (planner, engineer, architect) often need operational tools that enable adaptation scenarios to be analyzed quickly and with acceptable reliability.

A persistent challenge in urban climate modelling is the gap between high-fidelity research models and user-friendly operational tools. We outline several strategies to help overcome this divide:

- (i) Improved accessibility and documentation: High-resolution models often remain underutilised due to steep learning curves and lack of user-specific documentation. Tailored guides and simplified tutorials aimed at urban climate practitioners can significantly broaden model adoption.
- (ii) Cost and performance optimisation: The computational and financial costs of running complex models remain a barrier. Enhancing the efficiency of simulations (e.g., through model code optimisation or the use of local computing clusters) can reduce resource requirements while maintaining output quality.
- (iii) Hybrid and coupled modelling approaches: These allow modellers to reduce input data requirements and boundary condition complexity. By using pre-simulated datasets or coupling models of differing complexity, it is possible to maintain a balance between realism and feasibility.
- (iv) Simplified parameterisations from high-resolution models: Creating reduced-form models or parameterisations from validated high-resolution simulations can support integration into urban planning workflows. These simplified schemes retain essential physical realism while being compatible with planning tools.

By incorporating these recommendations, we aim to foster the development of modelling frameworks that are both scientifically robust and practically deployable, contributing to more effective and inclusive climate adaptation strategies at the urban scale.

5. Conclusion

The selected search equation has facilitated a comprehensive review of concepts, methodologies and models, available in the WOS, to describe (i) urban microclimates, (ii) vegetation properties and their influence on street-scale microclimatic conditions, and (iii) the additional role played by irrigation in modifying the thermal comfort of individuals. The most advanced Computational Fluid Dynamics (CFD) models seem particularly effective for assessing the effects of irrigated vegetation at the urban canyon scale. However, a significant gap in the literature persists concerning the ability of different irrigation regimes

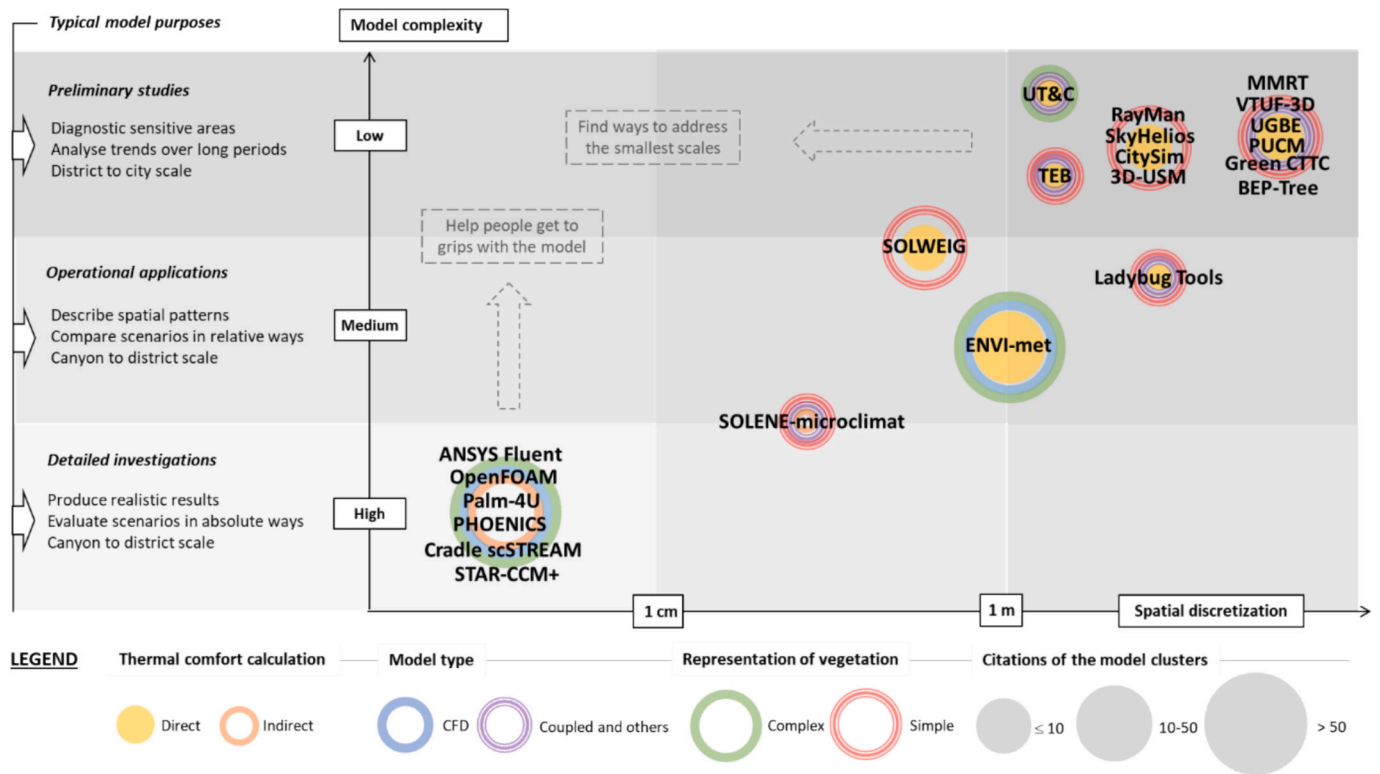


Fig. 8. Diagram showing the clustering of the 22 numerical models identified in this study. The clusters are classified based on their functionalities: direct or indirect calculation of thermal comfort, CFD or coupled models and others, complex vegetation representation (multiple effects of vegetation on the microclimate) or simple representation, and the number of citations of the models in each cluster. Additionally, the models are classified according to their typical usage purpose, complexity, and spatial discretization.

to partly control evapotranspiration rates from the vegetated areas, thus the cooling effects locally drawn from urban vegetation, whose arrangements and composition also deserve further studies.

A numerical and societal challenge is thus to develop robust and exportable models, both for heatwave mitigation and water management purposes, to arbitrate between different green grid set-ups and urban water uses. However, the dramatic lack of experimental data and standardized validation procedures, especially as regards the claimed thermal comfort indices, will most often leave the modellers and decision-makers with unevaluated uncertainties in the predicted determining physical variables. Those also prevent comparisons between models whose structure, aims and objectives may be different, from process understanding to operational planning purposes (urban microclimate management).

In the meantime, users are also encouraged to interpret the results wisely and strive to better understand the tools, their limitations, and strengths. This informed approach will help ensure more reliable and applicable outcomes in urban microclimate studies. Finally, there is a critical need to bridge the gap between academic research and operational practice, involving urban planners, engineers, and architects. Reliable and practical tools are essential to ensure that the insights gained from research can effectively be applied in real-world urban planning and development. This connection will foster the development of operational solutions that can better address the challenges of urban microclimates and resilient cities.

CRedit authorship contribution statement

Martina Garcia de Cezar: Writing – original draft, Methodology, Data curation, Writing – review & editing, Visualization, Formal analysis, Conceptualization. **Bruno Cheviron:** Writing – review & editing, Supervision, Data curation, Visualization, Methodology. **Severine**

Tomas: Visualization, Methodology, Writing – review & editing, Supervision, Data curation. **Merveil Muanda Lutete:** Visualization, Investigation, Conceptualization, Writing – review & editing, Validation, Formal analysis. **Auline Rodler:** Writing – review & editing, Project administration, Supervision. **Laurent Aprin:** Supervision, Writing – review & editing, Project administration.

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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.

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Data availability

Data will be made available on request.

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