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Review

Digital Approaches for Climate-Responsive Urban Planning: A Human-Centred Review of Microclimate and Outdoor Thermal Comfort

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Abstract

Rapid urbanisation and climate change are intensifying urban heat stress, posing significant challenges for climate-responsive urban planning. Digital and data-driven approaches, including GIS, remote sensing, microclimate simulation, and artificial intelligence (AI), have advanced urban climate analysis; however, their capacity to support human-centred planning remains insufficiently synthesised. This review analyses 78 peer-reviewed studies (2015–2025) to evaluate how digital methods address urban microclimate and outdoor thermal comfort. The reviewed studies are classified into four methodological groups: spatial data analytics, simulation-based models, parametric and optimisation workflows, and AI-driven or hybrid approaches. The results show that the majority of studies rely on proxy indicators, such as land surface temperature and sky view factor, while physiologically based comfort indices (e.g., PET and UTCI) are applied in a limited proportion of studies and remain largely confined to microscale simulations. A persistent scale mismatch is identified between large-scale analytics and pedestrian-level thermal experience, alongside geographic and climatic biases, particularly in hot-arid regions. Unlike previous reviews, this study integrates digital methodologies, urban microclimate processes, and human-centred thermal comfort within a unified framework. The findings provide actionable insights for planners and designers by supporting the integration of thermal comfort into multi-scale, climate-responsive decision-making.

Keywords: local climate zones; ENVI-met; urban heat island; mean radiant temperature; parametric urban design; explainable artificial intelligence

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1. Introduction

Rapid urbanisation, accelerating climate change, and intensifying heat stress are fundamentally reshaping the environmental performance and liveability of cities worldwide. Urban areas currently accommodate more than half of the global population and are projected to host nearly 70% by mid-century, amplifying pressures on land-use efficiency, energy systems, and environmental resilience [1,2]. Among the most pressing consequences of these trends is the intensification of urban heat, driven by dense built morphologies, impervious surfaces, diminished vegetation cover, and anthropogenic heat emissions. Elevated urban temperatures are associated with increased cooling energy demand, heightened outdoor thermal discomfort, heat-related morbidity and mortality, and a declining urban quality of life [3–5].

Urban heat and climate adaptation challenges are inherently multi-scalar and interdisciplinary. Decisions related to urban morphology, land-use distribution, building density, street geometry, vegetation structure, and material selection influence key microclimatic processes, including radiation exchange, airflow dynamics, shading patterns, and evapotranspiration, which in turn shape outdoor thermal comfort and human thermal perception [6–8]. However, conventional planning and land-use management instruments, such as zoning regulations, urban design guidelines, and performance-based planning codes, have largely relied on static zoning regulations, qualitative design guidelines, or aggregated performance indicators, limiting their ability to capture dynamic and scale-dependent climate–form–comfort interactions [9,10]. This methodological constraint becomes particularly consequential in heat-exposed regions, where extreme solar radiation and high mean radiant temperatures intensify the consequences of inadequate climate-sensitive planning.

In response to these challenges, digital and data-driven approaches have enabled the systematic analysis of urban microclimate processes across spatial scales, supporting higher-resolution modelling, improved predictive accuracy in machine-learning frameworks, and more efficient scenario evaluation. Advances in geographic information systems (GIS), remote sensing, urban climate modelling, parametric design, and computational optimisation have transformed how cities are analysed, simulated, and designed [11,12]. Earth observation datasets, land surface temperature (LST) mapping, and Local Climate Zone (LCZ) classification have enabled large-scale characterisation of urban thermal patterns and morphology–climate relationships [13,14]. At finer spatial resolutions, simulation-based tools, including ENVI-met, computational fluid dynamics (CFD), and urban building energy modelling platforms, allow the detailed assessment of microclimate dynamics, shading performance, airflow, and energy demand under alternative design scenarios [11,15,16].

More recently, artificial intelligence (AI) and advanced data-driven methods have been integrated into urban analysis workflows. Machine learning models, surrogate modelling techniques, and multi-objective optimisation algorithms increasingly support early-stage design exploration and accelerate computational processes [17]. Frameworks such as OptiMorph [18] demonstrate the potential of combining genetic algorithms, machine learning, and explainable artificial intelligence techniques, such as SHapley Additive exPlanations (SHAP), to optimise urban morphology across multiple performance metrics, including energy demand, solar access, sky view factor, and shading efficiency. These developments signal a transformative shift toward computationally enhanced planning and performance-based design.

Despite these advances, existing studies reveal several important limitations when examined from a climate-responsive and human-centred perspective. Large-scale geospatial analyses, including GIS- and remote sensing-based approaches, predominantly rely on proxy indicators such as land surface temperature (LST), urban heat island (UHI) intensity, Local Climate Zone (LCZ) classification, and sky view factor to characterise urban thermal conditions [13,14,19]. While effective for identifying city-scale patterns, these indicators do not adequately capture the microclimatic variability experienced at the pedestrian level, particularly with respect to mean radiant temperature, airflow, and humidity. Conversely, high-resolution simulation tools, such as ENVI-met and CFD, provide physically explicit representations of radiation exchange, ventilation, and shading processes [15,16], yet are typically applied to isolated case studies due to their computational intensity, limiting their scalability and integration into broader planning workflows.

While existing studies have demonstrated the capacity of digital tools to analyse urban thermal patterns across multiple spatial scales, important limitations remain in their ability to represent pedestrian-level thermal experience and support planning-oriented decision-making. In particular, large-scale geospatial approaches provide broad spatial coverage but rely on simplified proxy indicators, whereas high-resolution simulation models offer detailed physical representation but remain constrained in scalability and integration into planning workflows. Furthermore, the incorporation of physiological comfort indices and behavioural adaptation within digital frameworks remains inconsistent. These limitations highlight a critical gap between what is currently known, namely, the ability to model urban thermal conditions, and what remains insufficiently addressed, specifically the integration of human-centred thermal comfort into scalable, planning-relevant digital frameworks.

This divergence highlights a persistent scale mismatch between city-scale digital analytics and pedestrian-scale thermal experience. In addition, many digital frameworks remain predominantly energy-centric or form-driven, prioritising indicators such as energy demand, density optimisation, and solar access, while outdoor thermal comfort is often treated as a secondary outcome or represented through simplified proxies. Comprehensive comfort indices, such as Physiological Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI), which explicitly account for radiation, wind, humidity, and human physiology [20,21], remain insufficiently integrated into large-scale digital workflows. Furthermore, geographic and climatic biases are evident, with a concentration of studies in temperate and hot-humid regions, while hot-arid and semi-arid contexts, particularly in the Middle East and North Africa (MENA), remain underrepresented. Behavioural adaptation, cultural expectations, and vulnerable population groups are also rarely incorporated into digital modelling frameworks.

Parallel to advances in digital methodologies, a substantial body of urban climate research has articulated climate-responsive design strategies across multiple spatial scales, from material selection and vegetative cooling to street orientation, block configuration, and ventilation corridors [4,22]. Handbooks and guidelines provide extensive qualitative and semi-quantitative knowledge on how urban form can mitigate heat stress and enhance outdoor comfort [6]. However, implementation within planning practice remains fragmented. Evidence suggests that such strategies are often applied at small scales and are insufficiently embedded within formal planning instruments or regulatory frameworks [23]. This highlights a critical implementation gap between analytical capability and planning application.

This implementation gap underscores a key challenge: translating advances in digital urban climate analysis into operational, data-informed planning and design decisions. While digital tools support scenario testing and performance evaluation, their integration of urban microclimate processes, outdoor thermal comfort, and human behavioural adaptation within planning-oriented frameworks remains limited. This challenge is particularly critical in heat-exposed regions, where extreme thermal conditions constrain outdoor activity, social interaction, and urban liveability [24–26].

Against this backdrop, there is a clear need for a comprehensive and integrative review that critically synthesises digital and data-driven approaches to climate-responsive urban planning and land-use management, with particular attention to urban microclimate regulation and outdoor thermal comfort. Existing reviews often address digital tools, urban energy modelling, or AI-driven optimisation in isolation, without systematically linking them to human-centred thermal performance or to planning and design implementation [17]. Conversely, reviews of climate-responsive urban design frequently emphasise strategies and policies while engaging less deeply with emerging digital methodologies and computational workflows [22,23].

This review critically synthesises digital and data-driven approaches to sustainable urban and land-use management from a climate-responsive and human-centred perspective. The paper systematically classifies current methods into: (1) spatial data analytics (including GIS, LCZ mapping, and remote sensing), (2) simulation-based tools (e.g., ENVI-met, CFD, parametric modelling), (3) optimisation and generative design workflows, and (4) emerging AI-driven and hybrid techniques. Particular attention is given to how these approaches address urban microclimate processes, outdoor thermal comfort assessment, and human thermal perception, as well as their applicability across spatial scales and climatic contexts. The synthesis draws on a comparative analysis of 78 peer-reviewed studies, structured according to climate setting, geographic region, spatial scale, methodological architecture, comfort metrics, and planning relevance.

By foregrounding outdoor thermal comfort as a key performance indicator for sustainable urban development, this review bridges digital urban analytics, environmental physics, and behavioural adaptation. It advances a structured framework that clarifies scale, climatic, and human-centred gaps in current methodologies, identifies persistent implementation challenges, and outlines future research directions for integrating human-centred comfort into data-informed urban decision-making, particularly in heat-vulnerable regions.

2. Review Methodology

This review adopts a structured, transparent, and climate-focused methodology to synthesise contemporary research on digital and data-driven approaches for sustainable urban and land-use management, with particular emphasis on urban microclimate regulation and outdoor thermal comfort. In response to the growing complexity of urban heat challenges and the increasing reliance on computational tools in planning and design, the methodology integrates spatial analytics, microclimate simulation, optimisation-based workflows, and emerging artificial intelligence (AI)-driven techniques. This approach enables a comprehensive and human-centred synthesis of the literature.

To ensure methodological rigour and transparency, this review is informed by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) framework [27,28]. PRISMA has been increasingly adopted in built environment, urban climate, and sustainability review studies to enhance transparency in the literature selection and reporting processes (e.g., [8,29,30]). In this study, PRISMA principles are applied in a manner appropriate to a conceptual and integrative review, where the primary objective is to achieve thematic coverage, methodological classification, and analytical saturation, rather than exhaustive enumeration or statistical meta-analysis. The methodological approach aligns with a post-positivist epistemological stance, emphasising systematic appraisal, cross-comparison of methods, and critical interpretation of empirical, simulation-based, and data-driven findings.

2.1. Literature Search Strategy

The literature search was conducted across three major academic databases: Scopus, Web of Science (Core Collection), and ScienceDirect. These databases were selected for their complementary strengths in urban planning, urban climate science, environmental design, geospatial analysis, and computational modelling. Scopus served as the primary database due to its broad interdisciplinary coverage of peer-reviewed research on the urban climate, the built environment, and applied digital methodologies. Web of Science was used as a validation source to identify conceptually influential and highly cited studies published in leading journals. ScienceDirect was employed in a targeted, journal-led manner to capture recent and journal-specific publications within key built-environment and urban climate outlets.

It is acknowledged that ScienceDirect primarily indexes Elsevier publications, which may introduce a degree of publisher bias in the literature sample. However, this limitation is partially mitigated by the use of Scopus and Web of Science, which provide broad cross-publisher coverage. Future reviews may further expand database selection to include additional platforms to enhance comprehensiveness.

The review covers the period from 2015 to 2025, reflecting the consolidation and rapid expansion of digital urban climate research. This timeframe corresponds to major advances in geographic information systems (GIS) and remote sensing–based analytics, Local Climate Zone (LCZ) classification, urban microclimate simulation tools (e.g., ENVI-met and the Urban Multi-scale Environmental Predictor (UMEP)), parametric and optimisation-based urban design workflows, and AI-supported decision-support systems. It also aligns with key policy and methodological developments, including the post–Paris Agreement climate adaptation agenda and the increasing emphasis on urban heat resilience.

Search strings were constructed using Boolean operators to combine terms related to digital and data-driven methods, urban microclimate and heat-related processes, and urban form or land-use contexts. The exact Boolean search strings used for each database (Scopus and Web of Science) are provided in Table 1 to ensure transparency and reproducibility in accordance with PRISMA 2020 guidelines. ScienceDirect was searched using a targeted keyword-based approach aligned with selected high-impact journals. Records retrieved from Scopus and Web of Science were exported to a unified screening database, and duplicate entries were removed prior to screening.

Table 1. Literature Review Search Strategy: Digital and Data-Driven Urban Climate Research.

Category	Details
Databases	Scopus (primary); Web of Science Core Collection (validation); ScienceDirect (targeted journal-led search)
Search Strategy (Boolean Strings)	Scopus: (“urban microclimate” OR “urban heat” OR “urban thermal comfort” OR “heat exposure” OR UHI OR “mean radiant temperature” OR PET OR UTCI) AND (GIS OR “remote sensing” OR simulation OR “ENVI-met” OR CFD OR “urban modelling” OR “parametric design” OR optimisation OR “machine learning” OR AI) AND (“urban morphology” OR “urban form” OR “street canyon” OR “building height” OR density OR SVF OR shading OR ventilation OR “land use”) Web of Science: TS = (“urban microclimate” OR “urban heat” OR “urban thermal comfort” OR “heat exposure” OR UHI OR “mean radiant temperature” OR PET OR UTCI) AND TS = (GIS OR “remote sensing” OR simulation OR “ENVI-met” OR CFD OR “urban modelling” OR “parametric design” OR optimisation OR “machine learning” OR AI) AND TS = (“urban morphology” OR “urban form” OR “street canyon” OR “building height” OR density OR SVF OR shading OR ventilation OR “land use”) ScienceDirect: Targeted keyword-based search using combinations of “urban microclimate”, “thermal comfort”, “simulation”, “urban morphology”, and “digital tools” within selected high-impact journals in the built environment and urban climate fields
Time Frame	2015–2025 (reflecting the maturation of digital urban climate modelling, LCZ mapping, simulation-based design, and AI-supported planning tools)
Keywords and Logic	Combinations of terms related to digital and data-driven methods (e.g., GIS, remote sensing, simulation, AI), urban microclimate and heat-related variables (e.g., UHI, mean radiant temperature, shading, ventilation), and urban form or land-use context (e.g., urban morphology, street canyon, land-use planning)
Language	English
Document Type	Peer-reviewed journal articles only

The review was limited to English-language publications to ensure consistency in terminology, the comparability of findings, and the feasibility of systematic analysis. However, this may have resulted in the exclusion of relevant studies published in other languages. The overall search logic is summarised in Table 1.

2.2. Study Selection Criteria

A multi-stage filtering process, informed by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, was applied to ensure strict relevance to climate-responsive urban analysis. The initial screening of titles and abstracts excluded studies focused exclusively on indoor thermal comfort, building-scale optimisation without an urban context, or smart city technologies lacking explicit environmental or climatic assessment. Subsequently, full-text screening was conducted to further refine the dataset based on predefined inclusion and exclusion criteria, as summarised in Table 2.

Table 2. Inclusion and Exclusion Criteria.

Category	Criteria
Inclusion Criteria 1	Studies employing digital, computational, or data-driven methods (e.g., GIS, remote sensing, ENVI-met, CFD, parametric modelling, optimisation algorithms, AI/ML).
Inclusion Criteria 2	Studies addressing urban-scale, neighbourhood-scale, or pedestrian-scale environments.
Inclusion Criteria 3	Explicit consideration of urban microclimate variables (e.g., air temperature, mean radiant temperature, shading, wind, SVF).
Inclusion Criteria 4	Assessment of outdoor thermal comfort using comfort indices (PET, UTCI), adaptive models, or validated microclimate proxies.
Exclusion Criteria 1	Indoor-only comfort studies or HVAC-focused research without urban environmental context.
Exclusion Criteria 2	New-building design studies at architectural scale without surrounding urban morphology.
Exclusion Criteria 3	Purely technological or smart city studies lacking climate or thermal analysis.
Exclusion Criteria 4	Non-peer-reviewed literature or articles not published in English.

Outdoor thermal comfort indicators, such as Physiological Equivalent Temperature (PET), Universal Thermal Climate Index (UTCI), and thermal stress metrics, were not imposed as mandatory search keywords. Instead, these aspects were evaluated during the screening process to avoid excluding studies that address thermal comfort implicitly through microclimatic proxy indicators.

2.3. Screening and Selection Process

Following duplicate removal, records were subjected to a structured, multi-stage screening process designed to progressively refine the dataset toward studies that explicitly link urban morphology, microclimate processes, and outdoor thermal conditions. Screening focused on excluding purely descriptive mapping studies, remote sensing–only analyses lacking three-dimensional urban form or process-based interpretation, and research in which thermal analysis was peripheral, energy-only, or non-human-centred.

Screening continued until thematic saturation was achieved, that is, until additional studies no longer introduced new methodological categories, spatial scales, or analytical perspectives relevant to the review scope. The full screening logic and record reduction across stages are documented in the PRISMA flow diagram (Figure 1). Following eligibility assessment, the final corpus comprised 78 studies.

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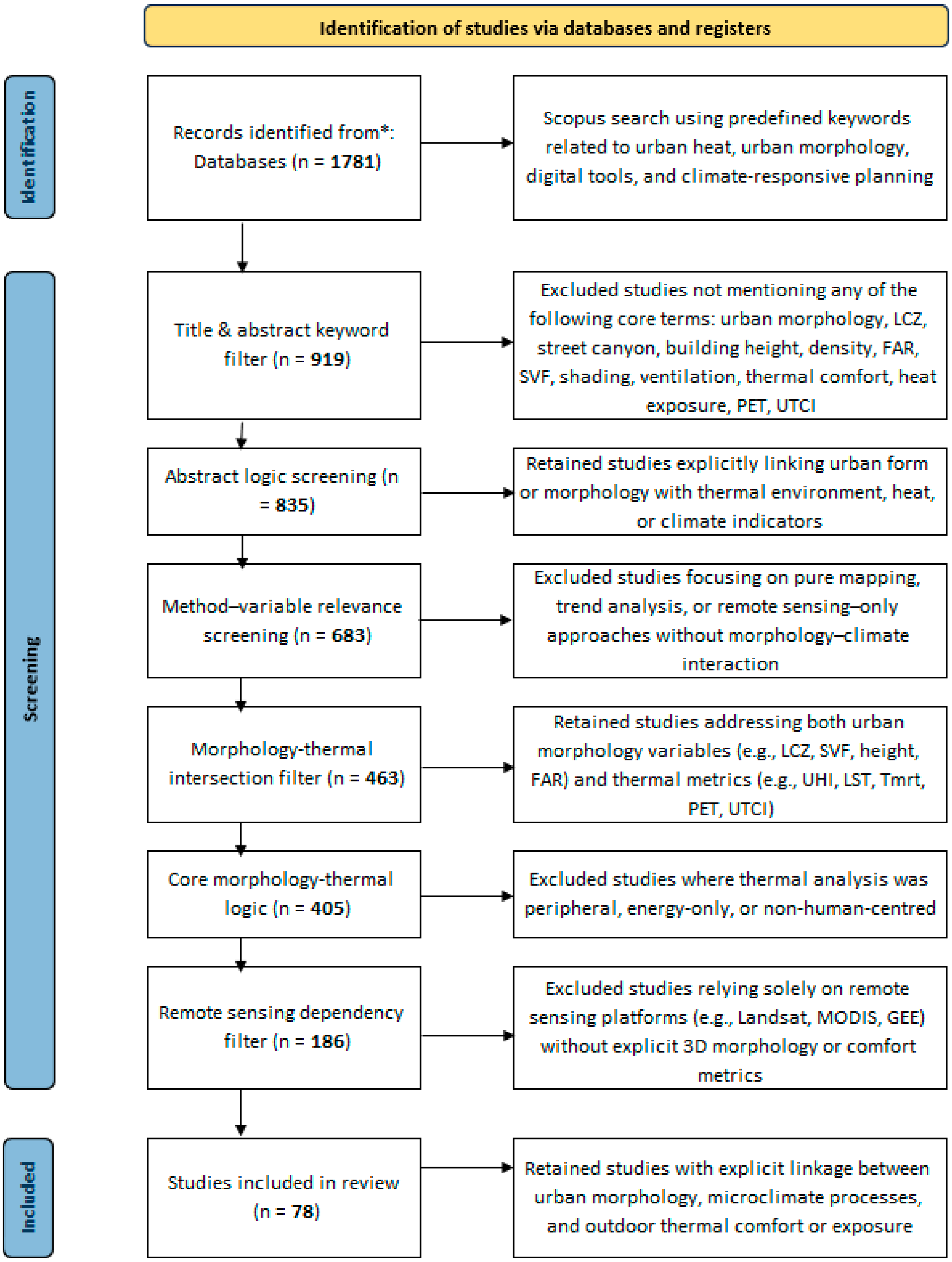

Figure 1. PRISMA informed multi-stage screening process illustrating search logic, exclusion criteria, and progressive refinement of studies included in the qualitative synthesis (n = 78). * Records identified from multiple databases (Scopus, Web of Science, ScienceDirect).

2.4. Data Extraction and Analytical Framework

Following screening, all eligible studies (n = 78) were analysed using a structured extraction protocol that captured climatic context and geographic region, spatial scale of analysis (street, block, neighbourhood, or city), the dominant digital or data-driven method employed (spatial analytics, simulation, optimisation, or artificial intelligence), and the urban morphology and land-use variables considered. The protocol further documented the microclimate indicators and thermal comfort metrics used, the degree to which human-centred thermal comfort was explicitly integrated, and the planning, design, or policy context in which the analysis was framed.

Studies were classified into methodological categories (spatial analytics, simulation-based modelling, optimisation/generative workflows, and AI-driven approaches) based on their dominant analytical workflow and primary methodological contribution. In cases where studies employed hybrid approaches, classification was determined by the principal method driving the analysis, while secondary methods were documented within the structured extraction dataset (Supplementary Table S1). This approach ensures consistency in categorisation while acknowledging the multi-method nature of contemporary digital urban climate research.

This structured dataset underpins the methodological classification presented in Section 3, the analysis of microclimate–comfort integration in Section 4, and the identification of methodological gaps and future research directions. A complete extraction table for all included studies (n = 78), detailing methodological attributes, spatial scales, variables, comfort metrics, and planning relevance, is provided as Supplementary Table S1.

2.4.1. Descriptive Characteristics of the Final Study Corpus

The climatic, geographic, and spatial-scale characteristics of the final dataset are summarised in Figures 2–4, which provide descriptive context for the subsequent methodological classification and thematic analysis. Figure 2 shows that the reviewed studies are predominantly situated in hot–humid and temperate climate contexts, with comparatively fewer investigations in hot-arid, cold, and multi-climate settings. Figure 3 indicates a strong geographic concentration of studies in East and Southeast Asia and Europe, while regions such as the Middle East and North Africa, North America, and South America are less frequently represented. Figure 4 illustrates that most studies operate at city and neighbourhood scales, with relatively limited emphasis on block, and street-scale analyses.

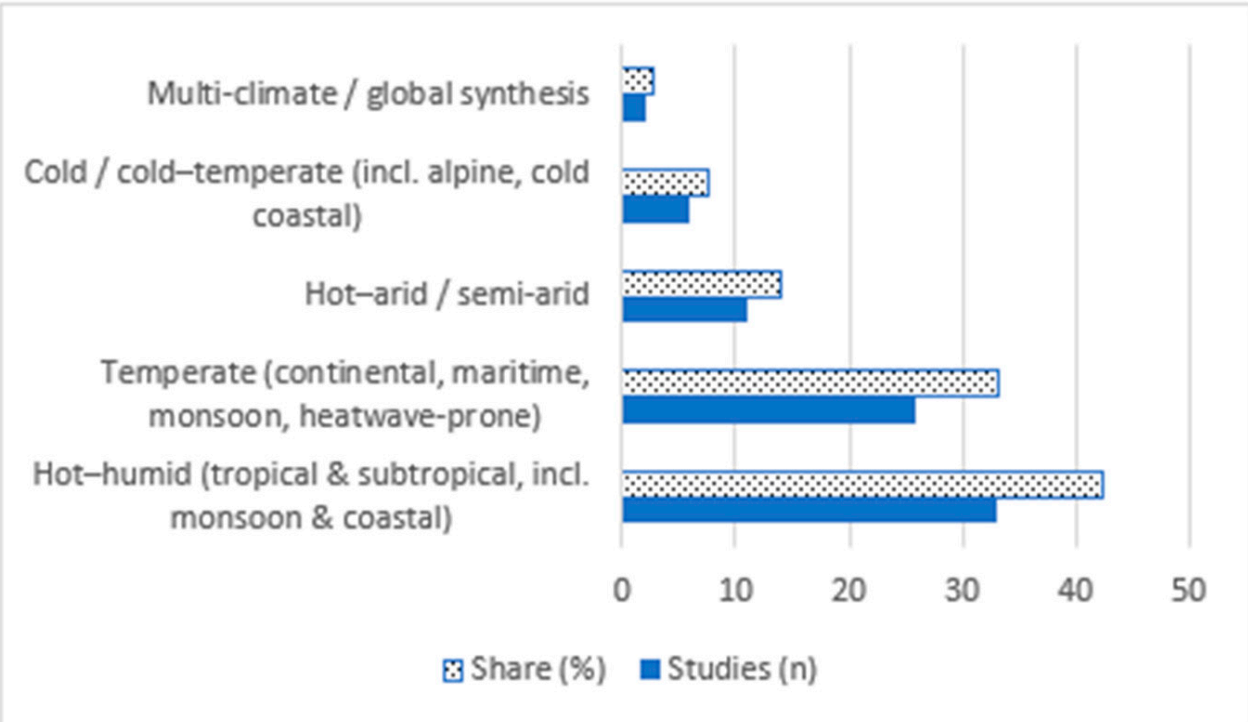

Figure 2. Distribution of reviewed studies by grouped climatic context, illustrating the climatic coverage of the final synthesis dataset (n = 78).

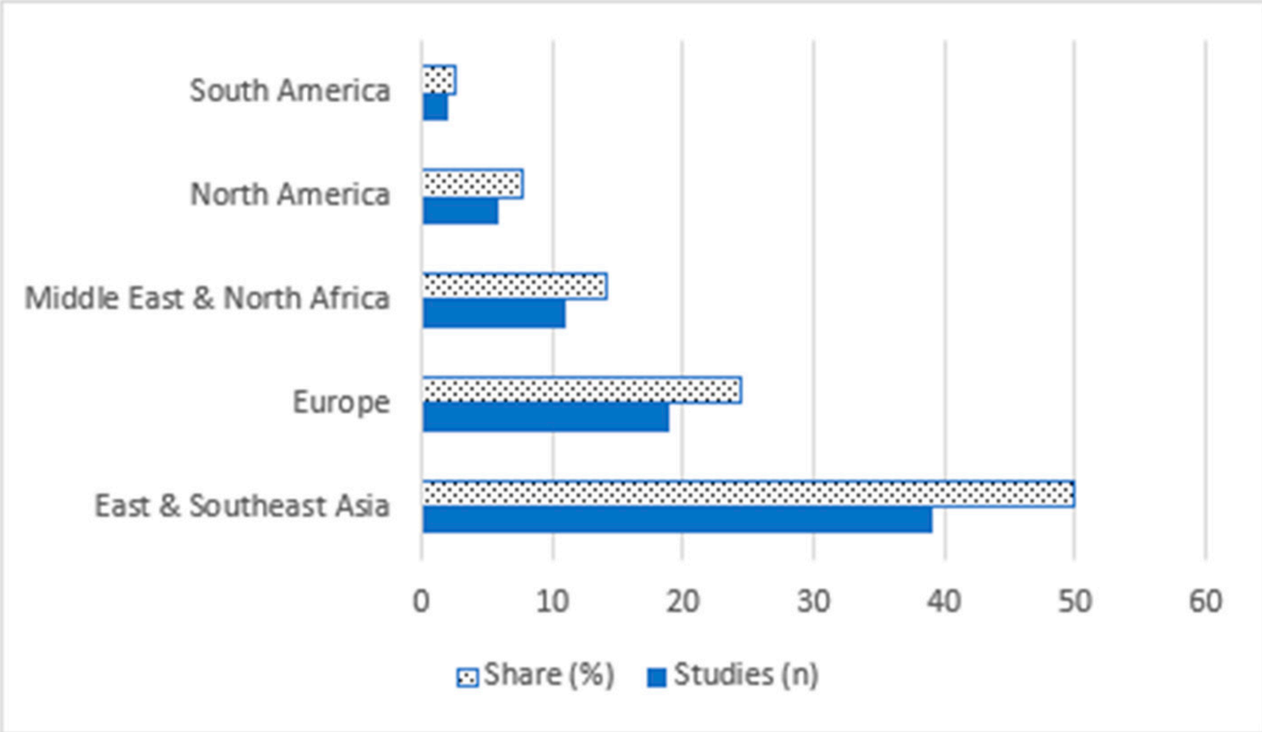

Figure 3. Geographic distribution of urban contexts examined in the reviewed studies, based on the final synthesis dataset (n = 78).

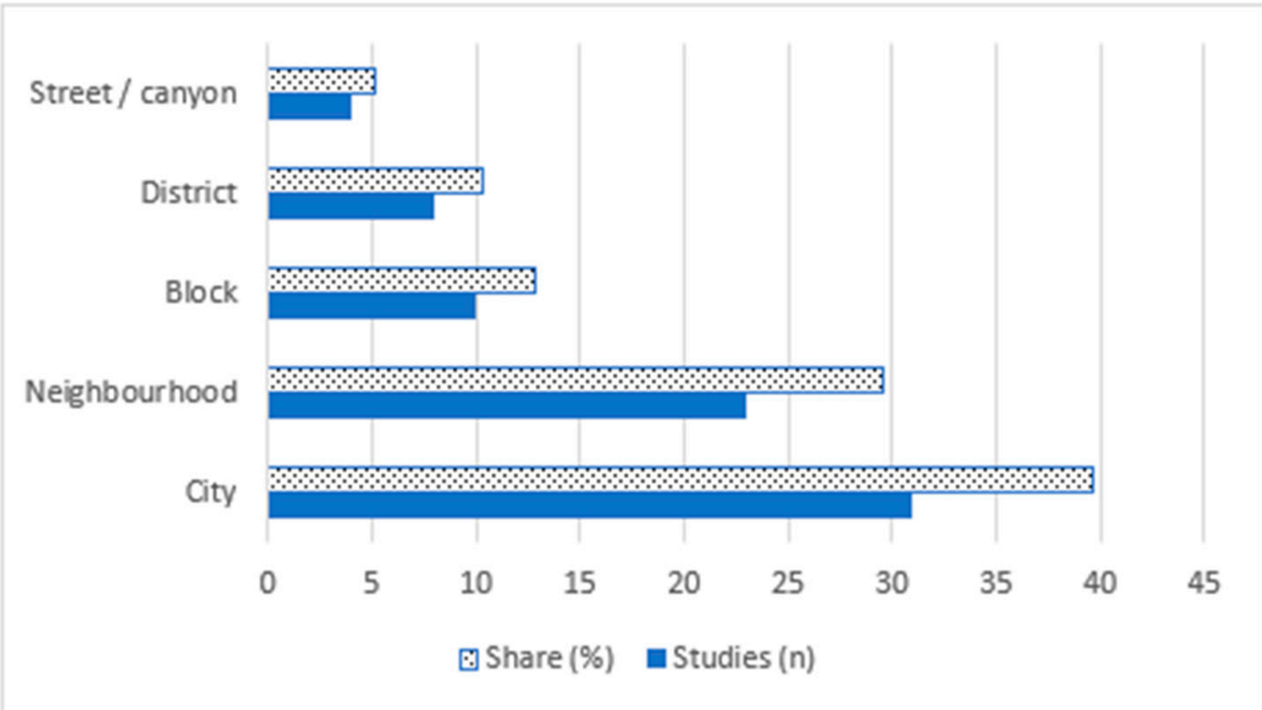

Figure 4. Distribution of reviewed studies by primary spatial scale of analysis, reflecting the analytical focus of the final synthesis dataset (n = 78).

2.4.2. Methodological Classification and Coding Framework

All eligible studies (n = 78) were analysed using a structured extraction protocol that captured climatic context and geographic region, spatial scale of analysis, dominant digital or data-driven method, urban morphology and land-use variables, microclimate indicators and thermal comfort metrics, degree of human-centred comfort integration, and planning or policy context. This structured dataset underpins the methodological classification presented in Section 3, the analysis of microclimate-comfort integration in Section 4, and the identification of methodological gaps and future research directions. A complete extraction table for all included studies is provided as Supplementary Table S1.

Studies were classified into four methodological categories, spatial data analytics, simulation-based modelling, optimisation and generative workflows, and AI-driven or hybrid approaches, based on their dominant analytical workflow and primary methodological contribution. This classification is grounded in the functional role of each approach within the urban climate modelling process. Spatial analytics primarily support large-scale data acquisition and pattern detection, simulation-based models provide physically grounded representations of microclimate dynamics, optimisation and generative workflows enable performance-driven design exploration, and AI-driven approaches facilitate data-driven prediction and integration across scales. This structure reflects both methodological distinctions and their operational relevance for planning and design, while accommodating the hybrid nature of emerging digital workflows. In cases where studies employed multiple methods, classification was determined by the principal approach driving the analysis, while secondary methods were recorded within the structured extraction dataset (Supplementary Table S1). This approach ensures consistency in categorisation while preserving the multi-method character of contemporary digital urban climate research. In addition, planning relevance was assessed using a qualitative coding framework that classifies studies into three levels: explicit, implicit, and limited. Studies were coded as explicit where direct connections to planning instruments (e.g., zoning regulations, building codes, or decision-support systems) were identified; implicit where design strategies or mitigation implications were discussed without formal policy integration; and limited where analysis remained primarily methodological or descriptive without clear planning application. The full coding criteria and indicators used in this classification are provided in Supplementary Table S2. This coding approach enhances the transparency, consistency, and reproducibility of the evaluation of planning relevance across the reviewed studies.

2.5. Synthesis Approach

Rather than ranking studies quantitatively, this review adopts a qualitative and comparative synthesis approach that focuses on identifying patterns, strengths, limitations, and research gaps across digital and data-driven methods, spatial scales, and degrees of integration between urban microclimate processes and outdoor thermal comfort. Studies are grouped according to methodological approach, analytical scale, and level of human-centred integration. This synthesis enables a critical examination of how digital tools support, or fail to support, climate-responsive and human-centred urban and land-use management and provides a robust foundation for the conceptual framework and research agenda developed later in the paper.

3. Digital Workflows for Urban Form–Microclimate Analysis

This section synthesises the reviewed literature by examining how different digital and data-driven workflows analyse urban form–microclimate relationships and their implications for outdoor thermal comfort. The reviewed studies are organised according to methodological family, analytical scale, and degree of human-centred comfort integration.

3.1. Overview of Methodological Classification and Analytical Dimensions

To structure the evidence from the 78 included studies, the reviewed literature was classified according to three complementary dimensions: (i) the dominant digital or data-driven workflow, (ii) the spatial scale and resolution at which urban form-microclimate relationships are analysed, and (iii) the extent to which analytical outputs move beyond thermal exposure mapping toward human-centred outdoor thermal comfort assessment.

Importantly, the purpose of this section is not to catalogue software or modelling platforms. Rather, each workflow family is critically examined in terms of how it addresses the core gaps identified in Section 1: (a) the under-integration of physiologically grounded outdoor thermal comfort (beyond proxy indicators such as LST), (b) the persistent disconnect between city-scale analytics and pedestrian-scale thermal experience, and (c) the limited translation of digital outputs into decision-ready guidance for planning and land-use governance, particularly in heat-vulnerable (e.g., hot-arid and semi-arid) contexts.

Across the dataset, a substantial proportion of studies operate at the city scale and at coarse-to-medium spatial resolutions, relying on geospatial predictors such as building height and density, floor area ratio (FAR), sky view factor (SVF), Local Climate Zone (LCZ) descriptors, and vegetation indices. These are commonly combined with surface-based thermal indicators derived from remote sensing and GIS workflows (e.g., [19,31–33]). A second major cluster integrates LCZ-based urban classification with machine learning and explainable artificial intelligence (XAI) to enhance the interpretability of morphology-temperature relationships (e.g., [34–36]). These studies typically operate at medium (30–100 m) or coarse (>100 m) spatial grids and focus on instantaneous or diurnal thermal characterisation.

In contrast, a smaller but methodologically significant body of work employs microclimate simulation tools, such as ENVI-met, urban weather generators (UWG), or computational fluid dynamics (CFD), either as primary analytical engines or within hybrid modelling pipelines. These approaches explicitly resolve wind, radiation, humidity, and mean radiant temperature, enabling the calculation of physiological comfort indices such as UTCI, PET, PMV, and SET* (e.g., [34,37–41]).

Emerging approaches further expand the methodological landscape through generative design and AI-assisted emulation. Examples include generative models coupled with microclimate simulation [42], hyper-fine (≤5 m) human exposure mapping [43,44], and image-based or sensor-supported XAI workflows that directly target pedestrian-scale comfort outcomes [45,46]. Figures 5–7 provide a high-level overview of these classification dimensions by illustrating the distribution of studies according to spatial resolution (Figure 5), temporal resolution of analysis (Figure 6), and dominant digital or data-driven approach (Figure 7). Together, these figures contextualise the methodological patterns discussed in Sections 3.2–3.5 and highlight the scale- and method-dependent treatment of urban microclimate and outdoor thermal comfort across the reviewed literature.

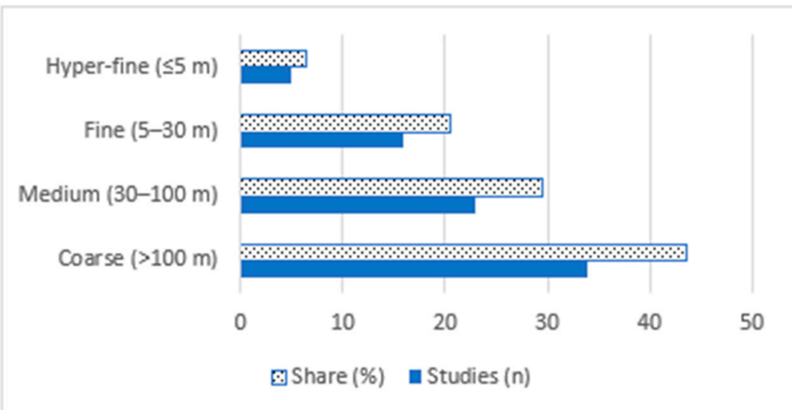

Figure 5. Spatial resolution and analytical scale of digital and data-driven approaches in the reviewed studies.

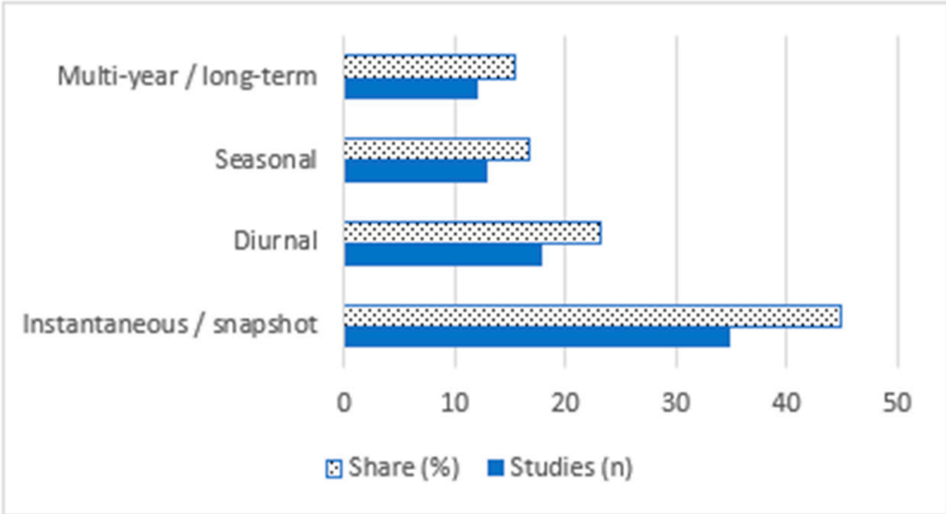

Figure 6. Temporal resolution of urban microclimate and outdoor thermal comfort analysis across methodological approaches.

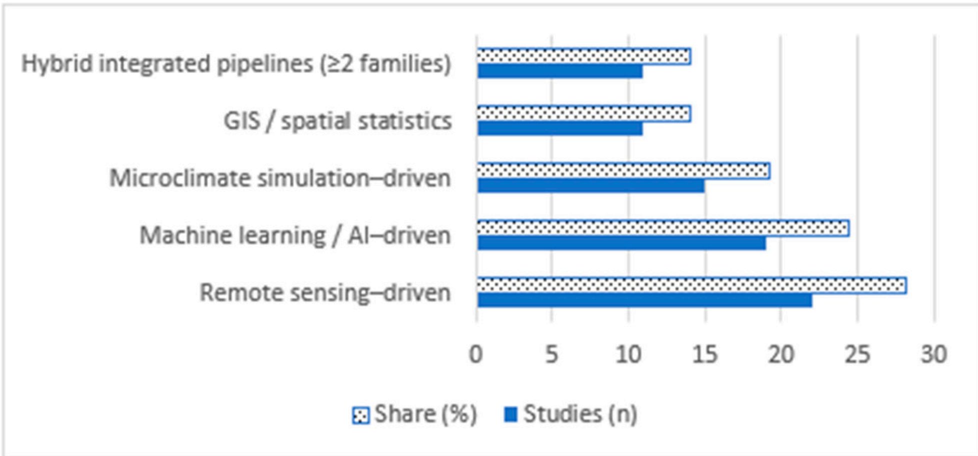

Figure 7. Distribution of reviewed studies by dominant digital and data-driven methodological approach.

To strengthen the comparative analysis, the reviewed methodologies are evaluated across key performance criteria, including their ability to accurately represent microclimate processes, their scalability across spatial extents, and their applicability within planning and design contexts. These criteria provide a structured basis for assessing the relative strengths and limitations of different approaches, ranging from large-scale spatial analytics to high-resolution simulation and AI-driven models. The comparative synthesis presented in Table 3 reflects these dimensions, enabling a more systematic evaluation of methodological performance and relevance for climate-responsive urban planning.

To improve clarity and enable systematic comparison across methodological families, Table 3 summarises the principal strengths, limitations, planning applicability, and degree of human-centred integration of each digital workflow. This comparative synthesis directly relates each approach to the core gaps identified in Section 1, namely scale integration, climatic contextualisation, and the incorporation of outdoor thermal comfort into planning-oriented analysis.

Taken together, these workflows should be understood as complementary rather than competing approaches. Emerging hybrid frameworks increasingly combine large-scale geospatial screening, targeted simulation, parametric design exploration, and AI-based upscaling to support climate-responsive and human-centred urban planning.

Table 3. Comparative evaluation of digital workflows for urban form–microclimate analysis and outdoor thermal comfort.

Workflow Family	Key Strengths	Key Limitations	Typical Spatial Scale	Human-Centred Comfort Integration	Planning Applicability
Spatial data analytics (GIS, remote sensing, LCZ)	Large-scale coverage; efficient hotspot detection; strong spatial comparability	Reliance on proxy indicators (LST/UHI); limited representation of radiation, airflow, and human perception	City/regional (≥30–100 m)	Low to partial	Strategic planning, zoning, heat-risk mapping
Simulation-based approaches (ENVI-met, CFD, UMEP, coupled models)	High physical realism; explicit modelling of radiation, airflow, and comfort indices (UTCI, PET)	High computational cost; limited scalability; site-specific application	Street/neighbourhood (≤30 m)	High	Design evaluation, scenario testing, microclimate-sensitive planning
Parametric and optimisation workflows	Systematic exploration of design alternatives; integration of performance trade-offs	Often rely on simplified comfort metrics; case-specific and designer-driven; limited policy transferability	Block/district (5–100 m)	Partial	Early stage design, masterplanning, performance-driven design
AI-driven and hybrid approaches	Cross-scale prediction; high computational efficiency; improved interpretability (XAI); scalable comfort modelling	Data-intensive; transferability challenges; limited integration into regulatory frameworks	Multi-scale (≤5 m to city scale)	Moderate to high	Decision-support systems, heat-risk prioritisation, adaptive planning

3.2. Spatial Data Analytics and Geospatial Approaches (Remote Sensing, GIS, LCZ Mapping, and Spatial Statistics)

This category includes studies in which the core analytical workflow relies on remote sensing, geographic information systems (GIS)-based urban morphology extraction, Local Climate Zone (LCZ) mapping, and/or spatial statistical analysis, often paired with conventional regression or classification techniques to explain urban thermal patterns. A substantial body of work continues to employ GIS- and remote sensing–based statistical approaches to characterise urban thermal behaviour and morphology–climate relationships. These studies are frequently operationalised through land surface temperature (LST), surface urban heat island (SUHI) and urban heat island (UHI) indicators, and LCZ descriptors at neighbourhood and city scales [47–53].

The dominant inputs in this family are plan- and block-scale urban form descriptors, including building height and density, floor area ratio (FAR), building coverage ratio (BCR), sky view factor (SVF), shading proxies, impervious and pervious surface fractions, vegetation indices (e.g., Normalised Difference Vegetation Index (NDVI)), and LCZ class labels. These variables are typically derived from building datasets and land-cover products (e.g., [19,32,47,49,52]). The approaches frequently rely on widely used Earth observation sources and platforms, such as Landsat products, the Moderate Resolution Imaging Spectroradiometer (MODIS), Google Earth Engine (GEE), and GIS environments, and are well suited to comparative mapping across large urban extents.

Across the reviewed dataset, geospatial approaches predominantly operate at city or neighbourhood scales, with spatial resolution typically in the medium (30–100 m) to coarse (>100 m) range, consistent with satellite-derived thermal products and LCZ grids. Representative examples include city-wide or grid-based analyses of thermal exposure using LST or UHI metrics [19,32], LCZ-based classification and statistical comparison of thermal conditions [47,54], and neighbourhood-buffer analyses linking morphology metrics to LST outcomes [48,49]. Temporal framing is most commonly instantaneous, relying on single-date or representative satellite scenes, with fewer studies explicitly addressing diurnal, seasonal, or longer-term dynamics [36,55]. As illustrated in Figures 4 and 5, geospatial approaches are therefore concentrated at medium-to-coarse spatial resolutions and are most often based on snapshot thermal characterisation, reflecting the constraints of satellite-derived products and LCZ-based analytical frameworks.

Typical outputs are dominated by thermal exposure mapping and morphology–temperature attribution, usually expressed as LST patterns, SUHI/UHI intensity, cooling intensity, or air temperature differentials where station-based or hybrid datasets are available. For example, GIS- and remote sensing-based workflows quantify LST-based cooling effects associated with parks or vegetation buffers [48] and identify LCZ-linked temperature contrasts at the city scale [47]. A more physically detailed geospatial sub-stream applies surface energy balance (SEB) decomposition to attribute SUHI intensity to radiative and heat-flux components at block-scale analytical units, while still producing exposure-oriented outputs rather than explicit comfort indices [52]. Across this family, reported comfort metrics are predominantly proxy-based (LST and UHI indicators), and the human-centred focus is largely partial or absent, reflecting limited engagement with physiological comfort indices or perceptual validation [19,47,49,52].

The main limitation of spatial data analytics and geospatial approaches is their continued reliance on exposure-centric indicators, which underrepresent key variables governing outdoor thermal comfort, particularly mean radiant temperature (Tmrt), wind speed, humidity, and their interaction within indices such as Universal Thermal Climate Index (UTCI), Physiological Equivalent Temperature (PET), Predicted Mean Vote (PMV), and Standard Effective Temperature (SET*). This constrains translation into pedestrian-scale design actions, as urban forms producing similar LST outcomes may generate substantially different radiant and ventilation environments. From a planning perspective, these studies are effective at identifying thermal hotspots and correlating land-cover or morphological attributes with elevated temperatures; however, they often provide limited guidance on how street-level geometry, shading strategies, or ventilation corridors should be configured to improve experienced thermal comfort. A related limitation is that city-scale remote sensing products typically support instantaneous or scene-based inference. Even where diurnal or long-term perspectives are incorporated, analyses tend to track thermal exposure indicators rather than comfort conditions linked to human activity patterns [36,55].

Nevertheless, planning relevance is frequently explicit within this family, as outputs are readily interpretable for zoning, greening prioritisation, LCZ-informed regulation, and strategic land-use decisions, even if human-centred comfort assessment remains indirect [19,32,47,48,52]. Taken together, spatial data analytics and geospatial approaches support city- and regional-scale thermal screening and strategic planning at medium-to-coarse spatial resolutions, typically ranging from 30 to 100 m grids to >100 m analytical units. However, they simultaneously exemplify the core gaps identified in this review. Their reliance on surface-based proxy indicators reinforces the conflation of thermal exposure with thermal comfort, while their coarse spatial and temporal resolutions limit representation of pedestrian-scale thermal experience. Consequently, although readily applicable to city-scale analysis and policy screening, these approaches only partially address human-centred outdoor thermal comfort and therefore require integration with finer-scale or hybrid methodologies to support climate-responsive urban design and land-use decision-making.

3.3. Simulation-Based Urban Microclimate and Coupled Climate–Energy Approaches

This category comprises studies in which the numerical simulation of urban microclimates and/or urban energy processes forms the analytical core. Unlike purely geospatial approaches, these methods explicitly resolve the physical processes governing outdoor thermal conditions, including radiation exchange, airflow, surface–atmosphere interactions, and vegetation effects. Within the reviewed corpus, the dominant tools include ENVI-met, computational fluid dynamics (CFD) solvers, the Urban Multi-scale Environmental Predictor (UMEP) and the Solar and Longwave Environmental Irradiance Geometry (SOLWEIG) model, as well as coupled climate–energy platforms (e.g., ENVI-met/EnergyPlus and ENVI-met/IES Virtual Environment (IES VE)). These tools are often supported by geographic information systems (GIS) for geometry preparation and scenario definition [36,56–58].

Scales covered. Simulation-based studies predominantly operate at micro to local scales, including street canyons, urban blocks, neighbourhoods, campuses, public spaces, and industrial complexes. Spatial resolution is typically fine (5–30 m) and, in some cases, hyper-fine (≤5 m) when detailed geometry or pedestrian-scale exposure assessment is required. Representative examples include street-canyon analyses in Turin [56], neighbourhood- and block-scale greening and geometry scenarios in Philadelphia [39] and Florence [57], and microscale shading and layout experiments in Chinese and Southeast Asian cities [58,59].

Temporally, simulations most often focus on diurnal or seasonal conditions associated with heat-stress events, rather than long-term climatological trends. Consistent with Figure 5, simulation-driven studies typically operate at fine to hyper-fine spatial resolutions to accurately resolve pedestrian-scale processes, including radiation exchange, shading dynamics, and airflow patterns, which are not captured by coarser geospatial approaches.

Given the diversity of numerical simulation tools employed across the reviewed studies, Table 4 provides a comparative synthesis of the principal simulation-based approaches. It summarises their typical spatial scales, modelling resolution, analytical strengths, and limitations, as well as their applicability to planning and design decision-making. This comparison highlights how different modelling environments address distinct aspects of urban microclimate processes and clarifies their respective suitability for pedestrian-scale analysis, neighbourhood planning, and strategic urban assessment.

Table 4. Comparison of Major Simulation-Based Urban Microclimate Modelling Approaches.

Model/ Approach	Primary Application	Typical Spatial Scale	Resolution	Key Strengths	Key Limitations	Planning Applicability	Representative Publications
ENVI-met	Urban microclimate and outdoor thermal comfort	Street–neighbourhood	0.5–5 m (typically)	Detailed radiation exchange, vegetation processes, MRT and comfort indices	High computational cost; limited simulation domain	Design evaluation and scenario testing	[39,56,57,60]
CFD Models	Airflow and urban ventilation analysis	Street–block	<1–5 m	High airflow and turbulence accuracy	High setup complexity; thermal–radiative coupling depends on configuration	Ventilation optimisation and morphology studies	[58,61,62]
SOLWEIG/ UMEP	Radiation balance and thermal exposure	Block–neighbourhood–district	1–10 m	Efficient radiation modelling with GIS integration	Simplified airflow representation	Rapid urban climate assessment	[63,64]
Coupled ENVI-met–EnergyPlus	Outdoor–building energy–microclimate interaction	Block–district	1–10 m	Integrated feedback between microclimate and building energy performance	Data intensive; workflow complexity	Climate-responsive planning and retrofit analysis	[65,66]
Urban canopy/district climate–energy models (e.g., UWG, CitySim)	District-scale climate–energy assessment	District–city	10–100 m	Scalability for strategic analysis	Reduced pedestrian-scale detail	Strategic planning and policy evaluation	[38,42,67,68]

The principal strength of this methodological family lies in its ability to generate physically explicit microclimate fields, including air temperature (Ta), mean radiant temperature (Tmrt), wind speed, humidity, surface temperature, and radiation fluxes. Consequently, this category demonstrates the highest uptake of direct outdoor thermal comfort metrics across the dataset. Many studies compute the Universal Thermal Climate Index (UTCI), Physiological Equivalent Temperature (PET), Predicted Mean Vote (PMV), and Standard Effective Temperature (SET*), either directly from simulation outputs or via post-processing modules [38,56–58,66]. This enables the evaluation of design interventions, such as tree canopy configuration, canyon aspect ratio, material albedo, and shading devices, based on experienced thermal stress rather than surface or canopy temperature alone.

Simulation-based approaches provide high physical fidelity and are generally considered more accurate in representing microclimate processes due to their explicit modelling of radiation, airflow, and heat exchange; however, validation against field measurements and transferability across different contexts remain limited in several studies. Despite their physical richness, these approaches exhibit two persistent limitations. First, they are computationally intensive and context-specific, typically applied to a limited number of representative sites or scenarios. This constrains scalability and complicates integration into routine city-wide planning workflows [56,57]. Typical simulation domains range from approximately 0.01 to 1 km^2, with computation times spanning several hours to multiple days per scenario, depending on grid resolution ($\leq$5 m) and model complexity, thereby restricting their applicability for large-scale, iterative urban analysis. Second, although thermal comfort indices are frequently reported, human adaptation and behavioural diversity, such as activity patterns, clothing insulation, and perceptual variability, are often simplified or assumed, with only a subset of studies incorporating surveys or perceptual validation alongside simulations [26,40,58]. As a result, thermal comfort is commonly treated as a physiological or physical state rather than a fully behavioural outcome.

At the same time, simulation-based studies demonstrate high design relevance because they allow direct testing of form-specific and controllable design variables, including street orientation, building height and spacing, vegetation type, shading structures, and material properties, and the enable quantification of their microclimatic and comfort impacts. As shown in Figure 8, planning relevance is predominantly explicit, particularly where simulations are framed as scenario-testing tools for urban regeneration, greening strategies, or climate adaptation measures [39,57,65,69]. However, translation into policy-scale instruments remains limited, as results are often site-specific and lack systematic linkage to zoning regulations or performance-based planning thresholds.

Illustrative studies from the dataset further demonstrate these capabilities. ENVI-met-based canyon and block analyses in Turin and Florence illustrate direct Universal Thermal Climate Index (UTCI)-based comfort assessment under alternative design scenarios [56,57]. Neighbourhood-scale greening and morphology simulations coupled with comfort indices are demonstrated in Philadelphia and Guangzhou [38,39]). Field-validated ENVI-met applications highlight the integration of measured data with simulation outputs to support pedestrian-scale comfort evaluation [40,58]. Coupled climate–energy workflows extend this category toward integrated performance assessment in hot-arid and semi-arid contexts [65,66].

Overall, simulation-based urban microclimate approaches represent the methodological family most directly aligned with human-centred outdoor thermal comfort assessment, as they explicitly resolve the physical processes governing pedestrian-scale thermal experience. However, their limited scalability, high computational demand, and site-specific implementation reveal a key structural gap identified in this review. While these models provide high physical realism, their integration into city-scale planning workflows and land-use decision-making remains constrained. Consequently, simulation-based methods effectively address the comfort dimension but only partially resolve the scale and implementation challenges required for operational climate-responsive urban planning.

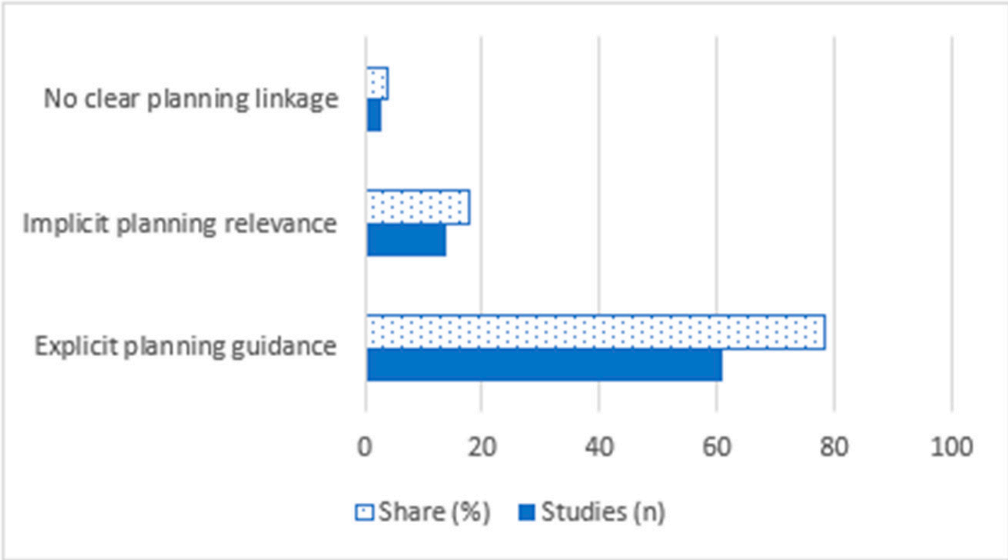

Figure 8. Distribution of planning relevance across reviewed studies, showing both the number of studies (n) and their proportional share (%).

3.4. Parametric, Optimisation, and Generative Design Workflows

Parametric, optimisation, and generative design workflows represent a methodological transition between physics-based simulation and data-driven intelligence, shifting the analytical focus from single-scenario evaluation toward the systematic exploration of urban design alternatives. Within this family of approaches, urban form variables are parameterized, often within computational design environments, and iteratively modified to evaluate trade-offs among microclimate performance, energy demand, and spatial configuration. Across the reviewed studies, such workflows typically rely on established simulation engines (e.g., ENVI-met, UWG, EnergyPlus, Ladybug, IES VE) as performance evaluators, while parametric modelling frameworks, optimisation routines, or generative algorithms are used to define and navigate the design space [42,66,70].

In these studies, urban morphology variables, including building height, floor area ratio, canyon aspect ratio, orientation, block typology, tree placement, and window-to-wall ratio, are explicitly encoded as adjustable parameters. These variables are systematically perturbed to generate multiple design scenarios, which are subsequently assessed against climate-related performance outputs. For example, Wang et al. [42] integrate generative adversarial networks (Pix2Pix and CycleGAN) with UWG and Rhino–Grasshopper to generate alternative block configurations and evaluate their microclimatic implications in Shenzhen. Similarly, Abdollahzadeh and Biloria [70] employ parametric optimisation workflows to explore district-scale urban typologies under heat-stress conditions in Sydney, using simulation feedback to compare thermal and energy performance across competing design options.

Studies in this category predominantly operate at block, district, and neighbourhood scales, where design flexibility remains high and geometric manipulation is computationally tractable. Spatial resolution is typically fine to medium (approximately 5–100 m), reflecting the need to resolve canyon geometry, shading patterns, and vegetation placement while still enabling iterative exploration. Temporal resolution is most often instantaneous or diurnal, focusing on representative hot-day or peak-stress conditions rather than long-term climatic averages [42,66,70].

Outputs from parametric and optimisation-based workflows tend to take the form of comparative performance landscapes rather than absolute predictions. Results are commonly expressed as relative improvements or trade-offs in air temperature, mean radiant temperature, shading duration, ventilation potential, or combined comfort-energy indicators. While some studies incorporate direct thermal comfort metrics, most notably UTCI, PET, or weighted comfort indices, many continue to rely on proxy indicators such as air-temperature reduction, shading ratios, or composite performance scores to guide optimisation processes [66,70]. As a consequence, the emphasis is placed on identifying better-performing design configurations rather than on fully characterising the diversity of human thermal experience at the pedestrian scale.

Despite their value for design exploration, parametric and generative approaches exhibit notable limitations with respect to comfort representation and planning applicability. Human-centred comfort considerations are often secondary to geometric or energy-based objectives, with comfort indices simplified or aggregated into composite scores that obscure experiential variation. Generative frameworks may, for instance, optimise shading or ventilation performance without explicitly accounting for behavioural adaptation or heterogeneity in thermal perception. Moreover, optimisation workflows are typically case-specific and designer-driven, limiting their transferability to regulatory or planning contexts. Outputs are rarely translated into explicit planning rules, zoning thresholds, or performance-based standards, thereby constraining their direct applicability to land-use governance and policy formulation [42,70].

Within the reviewed dataset, parametric and optimisation-based studies nonetheless demonstrate strong planning relevance, particularly for early-stage design support, climate-led masterplanning, and scenario testing [42,66]. However, their reliance on computationally intensive simulations and bespoke parametric models limits scalability beyond individual projects or districts. Consequently, these workflows function primarily as design decision-support tools rather than as city-wide decision-support systems. Conceptually, they occupy a critical intermediary position within the methodological spectrum: simulation outputs are no longer treated as end results, but rather as inputs to the structured exploration of the design space. This shift lays the groundwork for subsequent methodological developments, in which AI-driven and hybrid approaches aim to generalise, accelerate, and upscale optimisation logic across larger spatial and temporal domains.

Illustrative examples from the dataset further highlight this trajectory. Generative AI-assisted urban block modelling coupled with microclimate simulation is demonstrated by Wang et al. [42] in Shenzhen, while district-scale parametric optimisation under heat-stress conditions is explored by Abdollahzadeh and Biloria [70] in Sydney. Hybrid energy–climate optimisation incorporating comfort weighting is presented by Aghamolaei et al. [66] for neighbourhood-scale analysis in Tehran. Collectively, these studies illustrate how simulation-based microclimate assessment is increasingly used to inform the systematic exploration of urban form trade-offs, while simultaneously exposing the limitations that motivate the emergence of AI-driven and hybrid, data-centric workflows discussed in Section 3.4.

Taken together, parametric, optimisation, and generative design workflows illustrate an important methodological shift from analysing urban climate conditions toward actively exploring climate-responsive urban form alternatives. However, the reviewed studies also reveal a key limitation aligned with the research gaps identified in this review: although these approaches enhance design exploration and performance trade-off analysis, outdoor thermal comfort is frequently incorporated through simplified indicators or aggregated objectives rather than as a primary human-centred performance criterion. Moreover, their project-specific and designer-driven implementation limits transferability to broader planning or land-use governance frameworks. As a result, these workflows partially bridge the gap between physical simulation and planning application, yet remain insufficient for scalable, comfort-oriented urban decision-making without integration with data-centric or AI-driven approaches.

3.5. AI-Driven and Hybrid Data-Centric Approaches for Human-Centred Urban Climate Planning

Recent advances in artificial intelligence (AI)-driven and hybrid analytical frameworks represent a significant methodological shift in digital urban climate research. Unlike parametric and optimisation-based workflows (Section 3.3), which explore bounded design spaces through coupled simulations, AI-driven approaches seek to generalise relationships between urban form, climate, and human comfort. This enables scalable prediction, enhanced interpretability, and policy-relevant decision support across diverse spatial and climatic contexts.

As shown in Figure 7, AI-driven and hybrid data-centric approaches currently constitute a smaller share of the reviewed literature than geospatial and simulation-based methods. Their emergence nonetheless marks a clear methodological transition, reflecting both their relative novelty and their growing influence in advancing cross-scale integration, interpretability, and explicit modelling of outdoor thermal comfort.

The reviewed studies integrate machine learning, explainable AI (XAI), causal inference, surrogate modelling, and hybrid analytical pipelines combining remote sensing, GIS, Local Climate Zone (LCZ) classification, field measurements, and microclimate simulation. Common configurations include supervised machine-learning models coupled with XAI techniques, such as XGBoost, Random Forest, or LightGBM with SHAP or partial-dependence interpretation, hybrid ML-simulation frameworks that accelerate or emulate outputs from ENVI-met, UWG, or WRF, and data-centric or causal inference approaches (e.g., double machine learning) designed to isolate morphology-comfort relationships beyond correlation. Representative examples include LCZ-based explainable ML models linking urban morphology to UTCI at neighbourhood and city scales [34,36], hybrid UAV-LCZ-ML pipelines resolving fine-scale thermal heterogeneity [71], and ML-based surrogate models enabling high-resolution, city-wide thermal comfort mapping [44].

AI-driven approaches exhibit the widest spatial and temporal coverage among all methodological groups identified in this review. Applications range from hyper-fine pedestrian-scale analysis ($\leq$5 m), such as bus-stop-level UTCI exposure modelling [43] and street-level image-based comfort prediction [45], to neighbourhood- and city-scale predictive modelling based on LCZ grids, sensor networks, and multi-source geospatial datasets [72,73]. Several studies further extend analysis to regional or multi-city contexts, using AI to generalise heat-stress drivers across diverse urban and climatic settings [72]. As indicated in Figure 6, these studies increasingly move beyond snapshot-based thermal characterisation toward diurnal, seasonal, and multi-year representations, particularly where long satellite archives or dense sensor datasets are available.

A defining feature of this methodological family is its consistent engagement with outdoor thermal comfort. Compared with earlier approaches, AI-driven studies more frequently employ direct comfort indices such as UTCI, PET, and PMV, often supported by field measurements or perceptual data. Examples include explainable ML models identifying dominant morphological drivers of UTCI and PET under heat stress [46,74], image-based ML frameworks linking perceived sky, tree, and building visibility to UTCI at neighbourhood scale [45], and sensor-rich ML emulators producing hourly, city-wide thermal comfort maps suitable for planning applications [44]. The use of XAI techniques, such as SHAP values and partial-dependence plots, represents a critical advance by translating black-box predictions into interpretable relationships between urban form variables and human thermal exposure.

From a planning perspective, AI-driven and hybrid approaches offer several emerging strengths for climate-responsive urban and land-use management. These include computational efficiency and scalability for the rapid screening of large urban areas, cross-scale integration linking pedestrian-scale comfort to city- and regional-scale planning instruments, enhanced interpretability, and a growing emphasis on equity and human-centred assessment, particularly in addressing differential exposure across socio-spatial contexts [43]. Together, these attributes position AI-based frameworks as promising tools for performance-based planning, heat-risk prioritisation, and adaptive zoning strategies in heat-vulnerable regions.

Despite these advantages, important limitations remain. Many AI-driven models are data-intensive, relying on dense sensor networks or high-quality geospatial inputs that are not universally available. Transferability across climates, urban forms, and cultural contexts remains uneven, particularly where behavioural adaptation is weakly represented. Moreover, although interpretability has improved, robust causal attribution between urban interventions and comfort outcomes remains limited to a small subset of studies (e.g., [74]). Few AI-driven frameworks are fully embedded within formal planning or regulatory processes, highlighting a persistent gap between methodological capability and institutional adoption.

Overall, AI-driven and hybrid data-centric approaches represent the most advanced methodological frontier in digital urban climate research. By combining predictive power, interpretability, and explicit comfort modelling across scales, they offer a viable pathway toward genuinely human-centred, climate-responsive urban planning. Their effective translation into policy and practice, however, will require continued attention to data accessibility, model transparency, and governance integration, issues revisited in Section 4 and the concluding research agenda.

Viewed collectively alongside the preceding methodological families (Sections 3.1–3.3), AI-driven and hybrid approaches illustrate an emerging convergence between scalability, physical realism, and human-centred thermal comfort assessment. While geospatial analytics prioritise spatial coverage, simulation models provide physical fidelity, and parametric workflows enable design exploration, AI-driven frameworks increasingly attempt to integrate these capabilities within unified, cross-scale analytical systems. Nevertheless, the reviewed evidence indicates that achieving operational climate-responsive planning will depend not only on methodological advancement but on embedding outdoor thermal comfort as a governing performance objective across digital urban workflows rather than as a post-analytical outcome.

4. Integration of Urban Microclimate and Outdoor Thermal Comfort

4.1. Treatment of Urban Microclimate Processes

Across the reviewed literature, urban microclimate processes form the primary physical basis through which digital and data-driven approaches address climate-responsive urban analysis. These processes, most notably radiative exchange, airflow and ventilation, shading and solar obstruction, and evapotranspiration, mediate the relationship between urban form and outdoor thermal conditions. However, the depth, consistency, and physical completeness with which they are represented vary substantially across methodological families, spatial scales, and analytical toolchains.

This variation is reflected in the distribution of analytical tools and platforms employed across the reviewed studies (Table 4). GIS platforms and satellite remote sensing dominate the analytical landscape, indicating a strong reliance on spatial analytics and surface-based thermal observation. Machine-learning frameworks and LCZ-based classification approaches are also widely adopted, whereas physically explicit microclimate simulation tools and CFD-based airflow models are used far less frequently. This imbalance suggests that most studies prioritise scalability and spatial coverage over detailed process resolution, particularly with respect to radiation-airflow coupling and pedestrian-level dynamics.

At city and neighbourhood scales, spatial analytics and machine-learning-based approaches predominantly represent microclimate processes indirectly through surface-based or statistical proxies. Land surface temperature (LST), nighttime LST, and urban heat island (UHI) intensity are widely used to characterise the thermal behaviour of urban fabrics, often alongside land cover, vegetation indices (e.g., NDVI), and morphological descriptors such as building height, density, and LCZ class [19,32,33,36,75]. As shown in Figure 9, surface-based thermal indicators overwhelmingly dominate the set of microclimate variables considered, while variables directly governing human thermal exchange, such as wind, radiation balance, humidity, and energy fluxes, are incorporated far less consistently. This emphasis is reinforced by the dominance of geometric and density-related urban form descriptors, including building height, floor area ratio (FAR), and enclosure, whereas socio-spatial and functional variables remain comparatively underrepresented (Table 5). This distribution is further quantified in Table 6, which highlights the predominance of morphology- and density-based variables relative to socio-spatial descriptors across the reviewed studies. Consequently, multiple physical processes are frequently collapsed into aggregated exposure indicators, limiting causal interpretation.

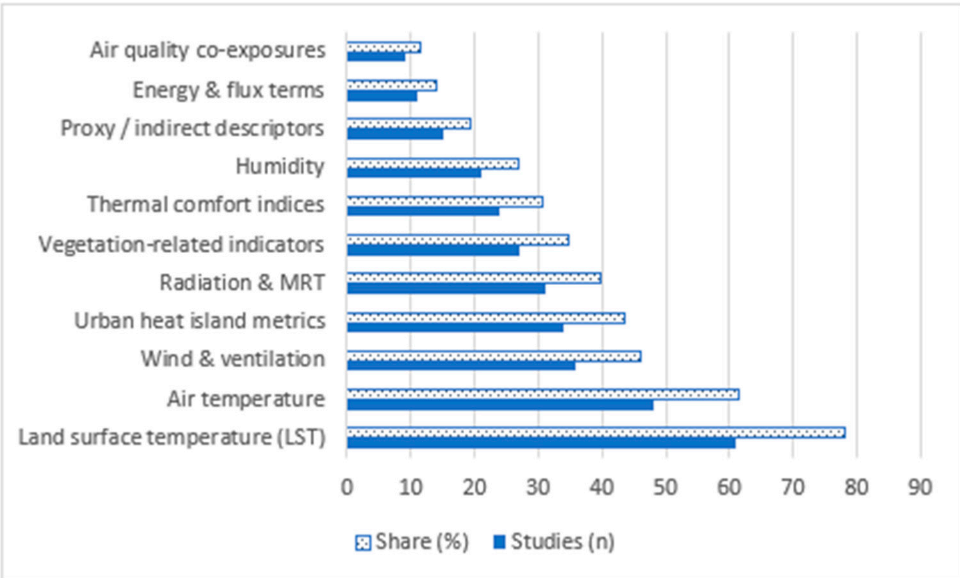

Figure 9. Distribution of microclimate variable categories across the reviewed studies (Bars indicate the number of studies and corresponding share (%) addressing each variable; categories are not mutually exclusive).

Ventilation and airflow processes are particularly underrepresented in large-scale data-driven studies. Although some city-scale analyses include wind speed or ventilation potential indices derived from simplified morphological metrics or network-based representations [33,76], airflow is rarely modelled as a dynamic three-dimensional process. Instead, it is approximated through static descriptors such as street orientation, sky view factor, or openness indices, urban form variables commonly included across the dataset (Table 5). These patterns are consistent with the variable frequency distribution presented in Table 6. This simplification constrains assessment of pedestrian-level wind comfort, pollutant dispersion, and convective heat removal under varying synoptic conditions.

Table 5. Tool and platform usage across the reviewed studies.

Tool Category	Studies Using Tool (n)
GIS platforms (ArcGIS, QGIS, etc.)	61
Satellite remote sensing (Landsat, Sentinel, MODIS, ECOSTRESS)	55
Machine learning frameworks (RF, XGBoost, LightGBM, DNN)	34
LCZ framework (incl. WUDAPT)	29
Microclimate simulation (ENVI-met, SOLWEIG, UWG)	26
Field sensors/monitoring	18
CFD/mesoscale models (WRF, FLUENT)	9

Note: Tools are non-exclusive; most studies employed multiple platforms within a single workflow.

Table 6. Frequency of urban form variables analysed in digital urban climate studies and their relevance to microclimate and outdoor thermal comfort assessment.

Urban Form Variable Group	Studies Including Group (n)
Building height/vertical form	65
Density/FAR/compactness	62
Sky View Factor and enclosure	48
Land cover and surface materials	44
Vegetation and blue–green infrastructure	41
Street geometry and orientation	29
LCZ-based morphological classes	27
Shading and solar obstruction	22
Functional/socio-spatial context	14

Note: Urban form variables are not mutually exclusive; most studies analysed multiple descriptors simultaneously. The distribution highlights the predominance of morphology- and density-based indicators in digital urban climate research, while socio-spatial and behavioural variables relevant to human thermal perception remain comparatively underrepresented.

In contrast, simulation-based microclimate models provide more physically explicit representations of urban microclimate processes. Tools such as ENVI-met, SOLWEIG (UMEP), CFD platforms, and urban weather generators explicitly resolve shortwave and longwave radiation exchange, shading dynamics, surface-air heat fluxes, airflow, and, in some cases, evapotranspiration and vegetation-atmosphere interactions [40,56,64,77]. Nevertheless, Table 4 shows that these tools remain marginal within the overall methodological ecosystem, highlighting a persistent trade-off between physical realism and scalability.

Hybrid workflows attempt to bridge this gap by coupling spatial analytics with microclimate simulation. LCZ-based modelling frameworks combined with ENVI-met or urban weather generators allow microclimate processes to be contextualised within broader urban typologies [38,39,78]. Similarly, remote-sensing-supported simulations integrate observed surface temperature patterns with physically based models to improve boundary conditions and spatial representativeness [61,62]. While these approaches enhance physical realism relative to purely statistical methods, they often retain a selective focus on temperature and radiation, with airflow and human-surface interactions remaining simplified.

Overall, the reviewed studies reveal a clear methodological gradient: large-scale spatial analytics prioritise efficiency and coverage but simplify microclimate physics, whereas high-resolution simulation tools achieve greater physical fidelity at the expense of scalability and planning integration. This uneven treatment of microclimate processes directly conditions how outdoor thermal comfort is subsequently represented, as examined in the following section.

4.2. Representation of Outdoor Thermal Comfort

While urban microclimate processes provide the physical foundation for climate-responsive urban analysis, the extent to which these processes are translated into outdoor thermal comfort assessment varies markedly across digital and data-driven approaches. Across the reviewed literature, outdoor thermal comfort is represented along a continuum ranging from indirect thermal proxies to explicitly modelled, human-centred comfort indices.

In addition to methodological differences, outdoor thermal comfort assessment is grounded in established theoretical models of human thermal perception. These include heat balance–based models, which account for the interaction between environmental variables (radiation, air temperature, wind speed, humidity) and human factors (metabolic rate and clothing insulation), as well as adaptive comfort models that consider behavioural and psychological adaptation. Widely used indices such as PET and UTCI are derived from these theoretical frameworks and provide a more comprehensive representation of thermal experience compared to proxy-based indicators. However, the reviewed studies show that these models are not consistently integrated into large-scale digital workflows, limiting their application in planning-oriented analysis.

4.2.1. Dominance of Proxy-Based Comfort Representation

A substantial proportion of the reviewed studies infer outdoor thermal conditions indirectly through proxy indicators rather than explicitly modelling human thermal experience. Surface-based metrics, particularly land surface temperature (LST) and urban heat island (UHI), related measures, dominate the analytical landscape [19,32,36,55,78]. This pattern is quantitatively confirmed by Figure 10, which shows that proxy-based indicators constitute the most prevalent form of comfort representation across the reviewed studies, while direct physiological comfort indices remain comparatively limited. Figure 9 further illustrates that LST and air temperature far exceed comfort-related variables in terms of adoption, reinforcing an exposure-centric framing of urban heat.

Although such proxies are effective for large-scale pattern detection and comparative assessment, they omit key determinants of human thermal perception, including wind speed, humidity, and mean radiant temperature. As a result, thermal exposure is frequently conflated with thermal comfort, limiting the relevance of findings for pedestrian-scale design and heat mitigation [75,79,80].

In several cases, proxy indicators are explicitly acknowledged as substitutes for comfort metrics due to data availability or computational constraints. For example, studies employing LCZ-based spatial analytics often interpret LCZ thermal signatures as indicators of relative comfort potential rather than direct measures of human thermal stress [47,54,81]. While this approach enhances scalability and comparability across large urban extents, it reinforces a surface-centric analytical perspective that marginalises human thermal perception and behavioural response, thereby constraining the integration of comfort as a primary analytical outcome.

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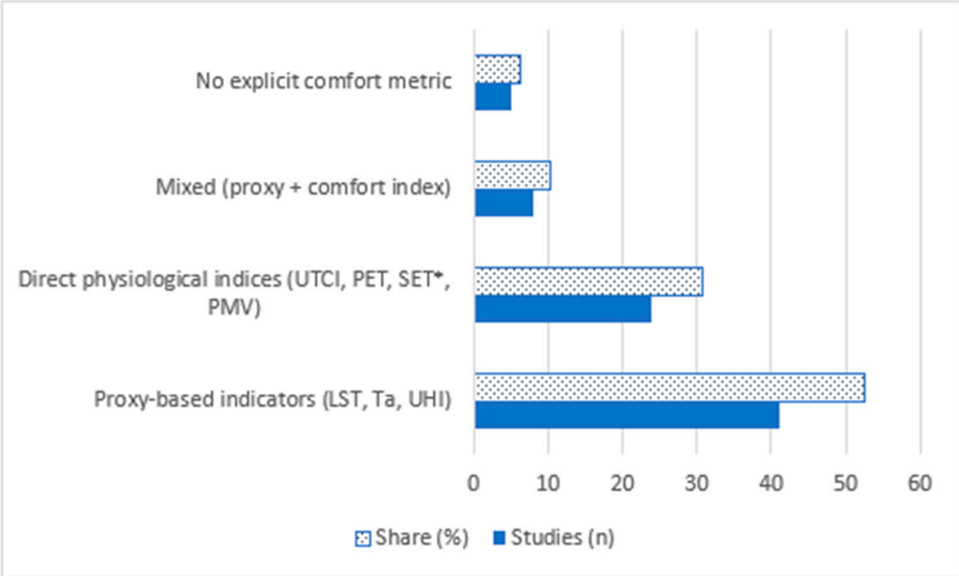

Figure 10. Distribution of outdoor thermal comfort metric types across the reviewed studies (n = 78). SET* refers to Standard Effective Temperature.

4.2.2. Partial Comfort Metrics and Hybrid Indicators

Between proxy-only approaches and fully human-centred assessments lies a group of studies that incorporate partial comfort indicators or hybrid representations. These studies typically combine air temperature with selected microclimate variables, such as wind speed or radiation, or infer comfort performance through indicators such as ventilation potential, cooling intensity, or shading effectiveness [61,76,78].

Such approaches improve upon surface-only proxies by acknowledging multivariable thermal dynamics, yet they often stop short of translating these variables into standardised comfort indices. For example, ventilation corridors are evaluated through airflow potential rather than comfort thresholds, and shading strategies are assessed via temperature reduction rather than perceived thermal relief [53,82]. This intermediate position is reflected in Figure 9, where wind, radiation, and humidity appear with moderate but inconsistent representation, indicating partial engagement with comfort-relevant physics without full human-centred integration. Consequently, comfort remains an implied outcome rather than an explicitly quantified performance criterion.

4.2.3. Adoption of Physiologically Based Comfort Indices

A smaller but methodologically significant subset of studies explicitly employs physiologically based outdoor thermal comfort indices, most notably UTCI and PET) [20,83]. As shown in Figure 10, direct comfort indices appear in fewer than one-third of the reviewed studies, underscoring their marginal status within mainstream digital urban analysis.

Simulation-based and hybrid workflows dominate this category, particularly at street and neighbourhood scales [38,39,56]. Studies that combine comfort indices with field measurements or perception surveys represent the most complete operationalisation of human-centred comfort [37,40,84].

Importantly, several studies integrate physiological indices with both microclimate measurements and human perception data, strengthening the validity of comfort assessment. For example, Fahy et al. [37], Schaefer et al. [40], and Mandelmilch et al. [84] combine PET-based modelling with on-site measurements and surveys, explicitly linking microclimate conditions to pedestrian thermal perception. Such approaches represent the most complete operationalisation of outdoor thermal comfort within the reviewed dataset.

4.2.4. Emerging Human-Centred and High-Resolution Approaches

Recent AI-driven and sensor-rich approaches demonstrate growing capacity to upscale comfort modelling. Image-based machine learning and surrogate models enable high-resolution UTCI mapping across larger spatial extents [43–45]. These advances directly respond to the imbalances evident in Figures 9 and 10 yet remain largely confined to data-rich contexts and experimental applications.

These approaches mark a critical methodological transition in which comfort indices are no longer restricted to small simulation domains but become increasingly scalable and interpretable. However, they are not yet widely embedded in planning instruments or regulatory frameworks.

4.2.5. Implications for Planning and Human-Centred Urban Design

Taken together, the reviewed studies indicate that outdoor thermal comfort remains unevenly represented across digital urban methodologies. Proxy-based indicators dominate large-scale analyses due to their efficiency and data availability, while physiologically grounded comfort metrics remain largely confined to fine-scale simulations or advanced hybrid workflows. This imbalance is reflected in Figure 11, which shows that only a minority of studies adopt an explicitly human-centred focus, while most either address comfort implicitly or remain limited to purely physical or environmental analysis. These patterns reinforce the scale disconnect identified earlier and constrain the translation of comfort research into land-use planning and zoning practice.

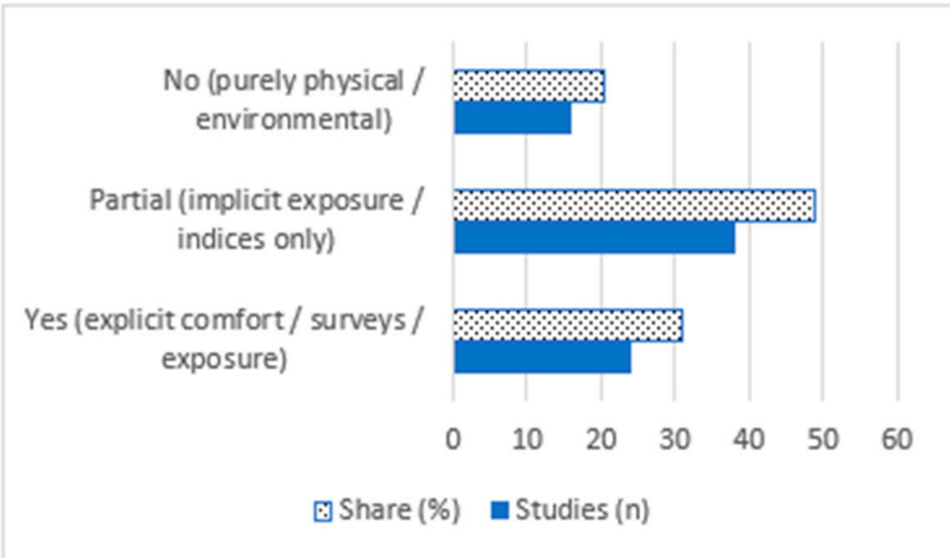

Figure 11. Distribution of studies by degree of human-centred outdoor thermal comfort focus (n = 78).

Studies that explicitly model comfort indices and validate them against human perception demonstrate greater relevance for design decision-making and climate adaptation planning. By engaging with pedestrian-scale experience, exposure duration, and behavioural response, these approaches support planning interventions that extend beyond thermal exposure mitigation toward improved outdoor liveability. However, as Figure 11 indicates, explicitly human-centred studies remain the exception rather than the norm, highlighting a structural gap between methodological capability and prevailing analytical priorities.

Bridging this gap requires methodological frameworks capable of integrating physically grounded comfort metrics across scales while maintaining computational tractability and interpretability for planners. Without such integration, digital urban climate tools risk reinforcing an exposure-oriented paradigm that is poorly aligned with human-centred design objectives and climate-resilient planning outcomes. The following section therefore examines how spatial and temporal scale mismatches further constrain the integration of outdoor thermal comfort into digital urban analysis, and why pedestrian-scale experience remains difficult to reconcile with city-scale planning tools.

4.3. Scale Mismatch and Resolution Challenges

A central challenge identified across the reviewed literature is the persistent mismatch between the spatial and temporal scales at which the urban climate is analysed and the scales at which outdoor thermal comfort is experienced and acted upon. Although digital and data-driven approaches have substantially expanded the analytical capacity of urban climate research, their application remains uneven across scales, limiting the integration of pedestrian-level thermal experience into planning-relevant decision-making.

4.3.1. Predominance of City-Scale and Coarse-Resolution Analyses

The majority of reviewed studies operate at city or neighbourhood scales using coarse or medium spatial resolutions (>100 m or 30–100 m grids). These approaches are typically grounded in GIS-based spatial analytics, remote sensing, or LCZ classification and are well suited for identifying broad thermal patterns, urban heat island hotspots, and long-term trends [19,31,55,71,81]. As such, they provide valuable strategic insights for regional planning, land-use allocation, and climate monitoring.

Earlier and mid-period studies frequently adopt medium-resolution grids or buffer-based analyses that remain insufficient to resolve pedestrian-scale thermal exposure, even when morphological complexity is acknowledged [54,55,80,85,86]. City-scale representations inherently smooth spatial heterogeneity and obscure microclimatic variability driven by street geometry, shading, vegetation structure, and material properties. Consequently, thermally critical conditions, such as extreme mean radiant temperatures or wind stagnation within street canyons, are often underrepresented or missed altogether. This limitation is particularly evident in studies relying on surface-based indicators such as LST or LCZ thermal signatures, which cannot resolve pedestrian exposure at the scale of human movement and activity [47,54,75].

4.3.2. Fine-Scale Comfort Assessment and Limited Scalability

In contrast, studies that explicitly assess outdoor thermal comfort typically operate at fine or hyper-fine spatial resolutions ($\leq$30 m), focusing on street canyons, blocks, or individual neighbourhoods. Simulation-based tools such as ENVI-met, SOLWEIG, and CFD enable detailed representation of radiation exchange, airflow, and shading, supporting the computation of comfort indices such as UTCI and PET [38,39,56,58].

While these approaches provide high-fidelity insights into human thermal experience, their computational intensity and data requirements restrict application to isolated case studies. As a result, comfort-focused analyses rarely extend beyond neighbourhood scale and are seldom embedded in routine planning workflows or city-wide assessments. This creates a structural divide in the literature: city-scale studies prioritise spatial coverage and generalisation, whereas pedestrian-scale studies prioritise physical accuracy and human relevance.

4.3.3. Temporal Resolution and Comfort Dynamics

Scale mismatch is further compounded by differences in temporal resolution. Many spatial analytics and remote sensing studies rely on instantaneous or temporally aggregated snapshots, often representing daytime or seasonal averages [32,85,87]. Although suitable for long-term trend analysis, such representations fail to capture diurnal variability, heatwave dynamics, or transient comfort conditions that shape real-world outdoor behaviour.

By contrast, studies incorporating diurnal or multi-temporal modelling, particularly those using sensor networks or high-resolution simulations, demonstrate that thermal comfort can vary substantially within a single day due to changes in solar radiation, wind conditions, and anthropogenic heat [37,84,88]. Nevertheless, temporally resolved approaches remain relatively rare and are typically confined to data-rich contexts.

4.3.4. Emerging Multi-Scale and Hybrid Approaches

Several recent studies attempt to bridge the scale divide through hybrid or multi-scale methodologies. LCZ-based frameworks combined with machine learning or sensitivity analysis enable the downscaling of city-scale thermal patterns toward neighbourhood-level interpretation [36,78]. Similarly, machine-learning-assisted emulators and explainable models offer promising pathways for approximating fine-scale comfort metrics across larger spatial extents [43,44].

However, structural limitations become evident when methodological maturity is examined alongside human-centred integration. As shown in Table 7, exploratory workflows dominated by remote sensing and GIS mapping are overwhelmingly associated with non-human-centred or only partially human-centred outcomes, despite their extensive spatial coverage. These approaches prioritise pattern detection and exposure mapping at city scale but rarely resolve pedestrian-level comfort processes.

Table 7. Crosstabulation of methodological tool maturity and degree of human-centred integration across the reviewed studies (n = 78).

Tool Maturity Level	No	Partial	Yes	Total
Exploratory (RS/GIS mapping)	12	17	4	33
Predictive (ML/simulation)	4	17	9	30
Human-centred (comfort, driven)	0	4	11	15
Total	16	38	24	78

Predictive workflows, including machine learning and simulation-based methods, demonstrate a modest shift toward partial human-centred integration, yet remain fragmented across scales. While these methods improve physical realism or predictive capability, they are often constrained to neighbourhood or case-study domains, limiting their relevance for city-wide planning instruments. Only a small subset of studies reaches a genuinely human-centred methodological tier in which comfort indices explicitly guide analysis and interpretation. Table 7 indicates that these comfort-driven approaches are almost exclusively associated with fine-scale or hybrid workflows, reinforcing the persistence of scale mismatch rather than resolving it.

Taken together, the evidence indicates that scale mismatch is not merely a technical limitation but a structural consequence of how methodological maturity, spatial scale, and human-centred intent are currently misaligned. Addressing this bottleneck requires digital frameworks that embed comfort-driven logic from the outset, rather than appending it at the final stage of analysis.

4.3.5. Implications for Climate-Responsive Planning

The observed scale mismatch has direct implications for climate-responsive urban and land-use management. Planning decisions are typically made at city or district scales, whereas thermal comfort is experienced at the scale of streets, public spaces, and pedestrian routes. When digital tools fail to reconcile these scales, planning interventions risk becoming either too generic to address local thermal stress or too localised to inform strategic policy.

Addressing this challenge requires methodological frameworks that integrate multi-scale representation, allowing coarse-scale screening to be systematically coupled with fine-scale comfort evaluation. Without such integration, outdoor thermal comfort is likely to remain marginal within digital planning workflows, reinforcing the gap between urban climate science and human-centred urban design.

The following section examines how this scale imbalance is further shaped by climatic and geographic biases within the literature, particularly the underrepresentation of heat-vulnerable regions and diverse socio-climatic contexts.

4.4. Climatic and Geographic Biases in Digital Urban Microclimate and Comfort Research

Despite the growing sophistication of digital and data-driven approaches to urban microclimate analysis, the reviewed literature exhibits pronounced climatic and geographic biases that constrain the generalisability and equity of current knowledge. Analysis of the 78 reviewed studies reveals a strong concentration of research in temperate and humid subtropical regions, particularly in East Asia and Europe, while hot-arid, semi-arid, and rapidly urbanising regions of the Global South remain comparatively underrepresented.

Long-term empirical and LCZ-based studies conducted in temperate and Mediterranean contexts further illustrate the dominance of proxy-driven thermal assessment and the limited uptake of comfort indices in planning-oriented research [64,75,79,80,83,89–93].

Across the dataset, humid subtropical and temperate monsoon climates dominate, with a substantial share of studies conducted in Chinese cities such as Beijing, Guangzhou, Wuhan, Hangzhou, and Shenzhen. These contexts frequently serve as testbeds for advanced digital workflows, including LCZ-based analytics, remote sensing-driven modelling, advanced micro-scale LCZ mapping approaches [94] and explainable machine learning frameworks (e.g., [34,36,75,95]). European cities, particularly in Switzerland, Italy, Germany, and the Netherlands, also feature prominently, often in studies employing high-resolution simulation tools or human-centred comfort indices such as PET and UTCI (e.g., [37,56,63]). While these regions provide valuable methodological benchmarks, their climatic conditions are not representative of the most heat-vulnerable urban environments globally.

In contrast, hot-arid and semi-arid climates, where extreme thermal stress most acutely affects outdoor activity, public health, and urban liveability, are addressed by a relatively small subset of studies. Examples include research conducted in Kabul [96], Dubai [80], Amman [97], Mashhad [60], Mexicali [98], Manama [65], and Tehran [66]. These studies often rely on land surface temperature-based proxies or simulation-driven exposure assessment, with fewer explicitly integrating human-centred comfort indices or behavioural adaptation. As a result, the methodological depth applied in temperate and humid contexts is not yet matched in climates where outdoor thermal comfort is most critical for urban resilience.

Geographic bias is further reflected in the spatial and socio-economic contexts represented. The majority of reviewed studies focus on formal urban fabrics, planned neighbourhoods, and data-rich metropolitan regions. Informal settlements, peri-urban areas, and rapidly expanding secondary cities, particularly in Africa, South Asia, and the Middle East, are rarely examined, despite their heightened vulnerability to heat stress and limited adaptive capacity. The study by Hussainzad and Gou [96] on informal settlements in Kabul represents a notable exception, highlighting both the feasibility and importance of extending digital microclimate analysis into underserved urban contexts.

Climatic bias also interacts with methodological choice. Advanced AI-driven and hybrid workflows, including explainable machine learning, surrogate modelling, and multi-scale integration, are disproportionately applied in regions with extensive data availability, dense sensor networks, and long-term remote sensing archives (e.g., [44,72]). Conversely, studies conducted in data-scarce climates tend to prioritise transferable but simplified indicators, such as LCZ classes or LST-derived metrics, which may inadequately capture pedestrian-scale thermal stress and adaptive behaviour.

Collectively, these biases underscore a critical misalignment between the geographic distribution of research effort and the global distribution of heat risk. While digital tools and data-driven methods have advanced rapidly, their application remains uneven, reinforcing knowledge asymmetries between well-instrumented cities and heat-vulnerable regions. Addressing this imbalance requires not only the transfer of established methodologies to underrepresented climates but also the adaptation of tools to account for data scarcity, informal urban form, and culturally mediated thermal perception. Without such efforts, the promise of human-centred, climate-responsive digital urban planning risks remaining confined to a limited set of climatic and geographic contexts.

4.5. Synthesis: Digital Urban Climate Tools Through a Human-Centred Lens

The preceding analysis reveals a persistent imbalance in how digital and data-driven approaches conceptualise, model, and operationalise urban microclimate and outdoor thermal comfort. Across spatial data analytics, simulation-based modelling, parametric design workflows, and emerging AI-driven frameworks, urban heat is overwhelmingly framed as a physical exposure problem, while human thermal experience remains weakly embedded in methodological design and planning interpretation.

Digital urban climate tools demonstrate strong analytical capacity in capturing dominant microclimate processes, particularly land surface temperature patterns, air temperature variation, and urban heat island intensity across neighbourhood and city scales. Remote sensing-based analytics and LCZ-driven frameworks enable the systematic comparison of urban thermal environments across large spatial extents and climatic contexts, while simulation-based tools provide detailed representations of radiative exchange, airflow, shading, and evapotranspiration at pedestrian scale. However, these strengths are unevenly distributed across scales, with no single methodological family capable of seamlessly linking city-scale pattern detection with street-level thermal perception.

The representation of outdoor thermal comfort remains methodologically fragmented. Although advanced comfort indices such as UTCI, PET, Tmrt, and SET* are increasingly applied in high-resolution simulations and field-based studies, they are rarely integrated into large-scale, data-driven analytical workflows. Instead, most city-scale and regional studies rely on proxy indicators, including land surface temperature, sky view factor, shading duration, or LCZ class, to infer comfort indirectly. While useful for comparative analysis, this reliance reinforces a conceptual conflation of thermal exposure and thermal experience, limiting interpretability for human-centred planning and design.

The analysis also highlights a systemic scale mismatch between digital analytical outputs and the spatial units of planning intervention. City-scale models often operate at grid resolutions exceeding 100 m or at administrative units that obscure street-level variability, while pedestrian-scale simulations remain computationally intensive and case-specific. Hybrid workflows that attempt to bridge this divide by coupling spatial analytics with microclimate simulation or by employing machine learning surrogates remain emergent and unevenly validated. As a result, thermal comfort knowledge is produced either at scales too coarse for design action or too fine for policy integration.

Climatic and geographic biases further constrain the generalisability and equity of current digital urban climate research. Hot-humid and temperate regions dominate the literature, while hot-arid, semi-arid, and Global South contexts, where outdoor thermal stress most directly affects daily life, remain underrepresented. Behavioural adaptation, cultural practices, and socio-environmental vulnerability are rarely incorporated into digital frameworks, even where advanced modelling techniques are employed, reinforcing a technocratic framing of thermal comfort detached from lived experience.

Despite these limitations, Figure 12 shows that the majority of reviewed studies explicitly claim planning relevance. This apparent alignment contrasts sharply with the limited operationalisation of comfort metrics, scale integration, and decision-ready outputs identified throughout Section 4. Planning relevance is therefore often asserted rather than structurally embedded within digital workflows.

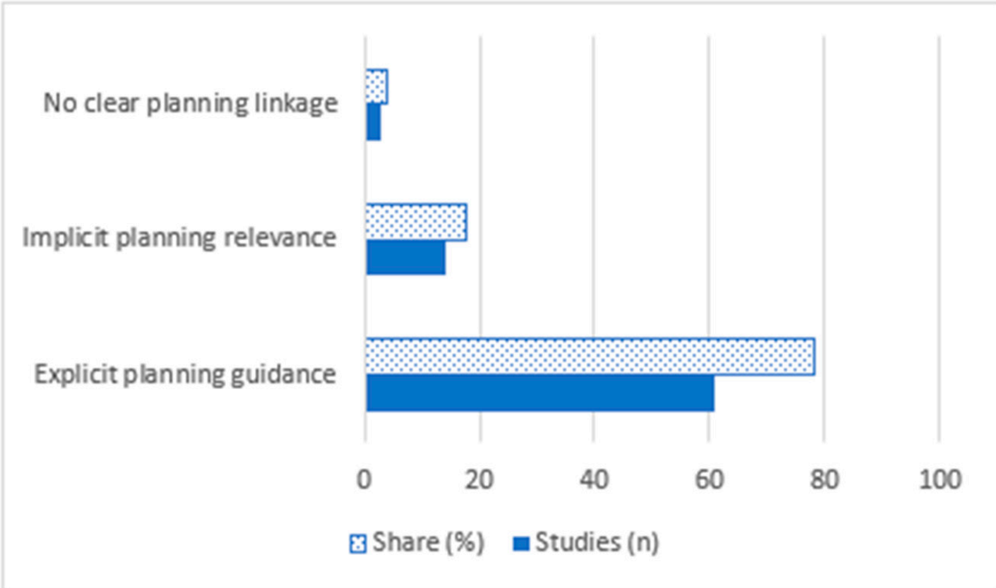

Figure 12. Distribution of planning relevance levels across the reviewed studies (n = 78).

Overall, the current generation of digital and data-driven urban climate tools is methodologically advanced but conceptually incomplete. Significant progress has been made in measuring, simulating, and predicting urban heat, yet translation into human-centred, planning-relevant knowledge remains limited. Comfort metrics are frequently appended rather than embedded, and planning relevance remains more declarative than operational.

This synthesis reinforces the central argument of this review: outdoor thermal comfort must be repositioned from a secondary outcome to a core organising principle in digital urban analysis. Achieving this shift requires not only improved metrics or higher-resolution data but also a fundamental rethinking of how digital tools align scale, climate physics, human perception, and planning logic. The following discussion (Section 5) builds on this synthesis to examine why these gaps persist, how methodological and institutional barriers constrain translation into practice, and what directions future digital urban climate research must take to support climate-responsive, human-centred urban and land-use planning, particularly in heat-vulnerable regions.

4.6. Toward an Operational Framework for Human-Centred Thermal Comfort Integration

While the preceding synthesis highlights persistent gaps in the integration of urban microclimate processes and outdoor thermal comfort, it also points toward the need for a more structured and operational approach capable of linking environmental analysis with planning and design decision-making. This section proposes a conceptual framework that integrates physical microclimate variables, physiological comfort indices, and behavioural and socio-cultural dimensions within a coherent and scalable analytical structure.

4.6.1. Linking Physical Processes, Comfort Indices, and Human Experience

Urban thermal environments are governed by the interaction of key physical variables, including radiation exchange, airflow dynamics, humidity, and surface-atmosphere heat fluxes. These variables determine environmental conditions at the pedestrian level and are translated into human thermal experience through physiologically based comfort indices, most notably the Universal Thermal Climate Index (UTCI) and the Physiological Equivalent Temperature (PET).

However, outdoor thermal comfort is not solely a function of environmental exposure. Behavioural adaptation (e.g., clothing, activity patterns, temporal avoidance), socio-cultural expectations, and perceptual factors significantly influence how thermal conditions are experienced. As a result, a comprehensive human-centred framework must integrate three interdependent layers:

(i) physical microclimate processes,
(ii) physiological comfort indices, and
(iii) behavioural and socio-cultural adaptation.

Across the reviewed literature, these layers are rarely integrated systematically, with most studies focusing on one or two dimensions. This fragmentation limits the ability of digital workflows to support planning-relevant, human-centred decision-making.

4.6.2. Levels of Integration in Digital Urban Climate Workflows

To clarify the current methodological landscape and provide a pathway toward operationalisation, three levels of integration can be identified:

Level 1: Exposure-based (basic integration).

This level is characterised by the use of proxy indicators such as land surface temperature (LST), urban heat island (UHI) intensity, and LCZ-based thermal classification. These approaches, typically implemented through GIS and remote sensing, enable large-scale spatial analysis and are effective for identifying thermal hotspots. However, they do not explicitly represent human thermal perception and therefore capture thermal exposure rather than thermal comfort.

Level 2: Process-informed (intermediate integration).

At this level, studies incorporate selected microclimate variables, including air temperature, wind speed, and shading, often derived from simulation or hybrid workflows. While these approaches improve physical realism and capture multivariable interactions, they typically rely on partial or indirect comfort indicators. Consequently, thermal comfort remains an inferred outcome rather than an explicitly quantified metric.

Level 3: Human-centred (advanced integration).

The most advanced approaches explicitly integrate physically based microclimate modelling with physiological comfort indices (e.g., UTCI, PET), and in some cases behavioural and perceptual data obtained through field measurements or surveys. These methods provide the most complete representation of pedestrian-scale thermal experience and are directly relevant to urban design and climate adaptation. However, their application remains limited in scale and is not yet systematically embedded within planning frameworks.

This three-level structure highlights that advancing digital urban climate analysis requires not only increased technical sophistication but also a progressive shift toward embedding human-centred performance within methodological design.

4.6.3. Toward Operational Integration in Planning Frameworks

To support climate-responsive planning, the integration of microclimate processes and thermal comfort must be translated into decision-support workflows that connect environmental analysis with planning instruments. This requires linking physical variables, comfort indices, and human behaviour to planning-relevant outputs such as zoning criteria, design guidelines, and performance thresholds.

Existing approaches in environmental planning provide useful precedents. Ecosystem-based frameworks, such as the Mapping and Assessment of Ecosystems and their Services (MAES), demonstrate how biophysical variables, environmental impacts, and human well-being can be integrated within spatial planning using GIS-based analytical tools [99]. These approaches provide a transferable methodological basis for linking environmental processes with decision-making.

Building on this logic, a climate-responsive urban framework can be conceptualised as a multi-stage workflow in which:

- large-scale spatial analytics identify thermal exposure patterns and priority areas,
- simulation and hybrid models resolve microclimate processes and compute comfort indices at relevant spatial scales, and
- human-centred interpretation incorporates behavioural adaptation, temporal use patterns, and socio-cultural context to inform planning and design decisions.

Such an approach enables a transition from descriptive and predictive analysis toward performance-based planning, where outdoor thermal comfort becomes an explicit and measurable objective.

4.6.4. Implications for Climate-Responsive and Human-Centred Urban Design

The proposed framework reinforces the need to reposition outdoor thermal comfort as a core performance criterion in urban planning and design. Integrating comfort-driven metrics across spatial and temporal scales enables alignment between city-scale analysis and pedestrian-scale experience, directly addressing the structural scale mismatch identified throughout this review.

Moreover, incorporating behavioural and socio-cultural dimensions ensures that planning strategies reflect not only environmental conditions but also patterns of use, adaptation, and vulnerability. This is particularly critical in heat-vulnerable regions, where outdoor thermal conditions directly influence public health, social interaction, and urban liveability.

Importantly, the framework establishes a structured linkage between physical microclimate variables, physiological comfort indices, and human-centred behavioural responses, thereby moving beyond exposure-based assessment toward an integrated, decision-relevant understanding of urban thermal environments.

Ultimately, advancing toward human-centred digital urban climate workflows requires embedding multi-layer integration within planning processes and supporting it with scalable, interpretable, and data-informed tools. By structuring this integration explicitly, the proposed framework provides a foundation for translating analytical advances into operational strategies for sustainable and climate-resilient urban development.

Building on this integrative conceptual framework, the following section translates these relationships into operational planning pathways by linking digital analytical approaches with strategic, tactical, and operational levels of urban decision-making.

5. Discussion: From Digital Analysis to Climate-Responsive and Human-Centred Urban Planning

This review set out to critically examine how digital and data-driven approaches contribute to sustainable urban and land-use management when evaluated through the lens of urban microclimate regulation and outdoor thermal comfort. The synthesis of 78 studies reveals substantial methodological innovation but also exposes persistent structural gaps that constrain the translation of digital urban climate analysis into human-centred planning and design practice. Building on the evidence presented in Sections 3 and 4, this discussion addresses four interrelated questions: (i) why outdoor thermal comfort remains marginal in digital urban workflows, (ii) why scale integration continues to be problematic, (iii) why planning uptake remains limited despite technical advances, and (iv) what directions are required to operationalise climate-responsive, comfort-oriented digital planning frameworks.

5.1. Persistent Marginalisation of Outdoor Thermal Comfort

Despite growing recognition of heat stress as a major urban sustainability and public health challenge, outdoor thermal comfort remains weakly integrated into most digital urban analysis frameworks. As demonstrated in Section 4, thermal conditions are predominantly represented through proxy indicators, such as land surface temperature (LST), sky view factor (SVF), or shading duration, which are widely derived from remote sensing and morphological analysis workflows [100,101], rather than through physiologically grounded comfort indices such as PET or UTCI (see Figures 8 and 9). While proxy-based approaches are computationally efficient and well suited to city-scale analysis, they fail to capture the combined effects of radiation, wind, humidity, and human physiology that determine thermal perception at the pedestrian level.

This marginalisation is not merely a technical limitation but reflects a deeper epistemological bias within digital urban research. Many data-driven and optimisation-oriented studies prioritise variables that are readily observable through remote sensing or easily parameterised in spatial models, whereas human thermal comfort requires more complex coupling between microclimate physics and behavioural response. This limitation is well documented in recent reviews highlighting the inability of current comfort indices to capture psychological, behavioural, and multi-sensory influences on thermal perception [102]. Consequently, comfort is often treated as an implicit by-product of morphological optimisation rather than as an explicit performance criterion guiding urban form decisions. This finding reinforces the first research gap identified in Section 1 and aligns with earlier exposure-oriented traditions in urban climate research, particularly within large-area remote sensing, LCZ-based, and monitoring-based studies [50,51,86,89,90,92,93,103].

5.2. Scale Fragmentation and the City–Pedestrian Divide

A central finding of this review is the persistent scale mismatch between digital urban climate analytics and human thermal experience. City- and neighbourhood-scale approaches, particularly GIS- and LCZ-based workflows, offer valuable insights into spatial patterns of heat exposure and the morphological drivers of thermal variability. However, their typical spatial resolutions (>100 m) and temporally aggregated representations obscure critical microclimatic processes, including radiant heat exchange, street-level ventilation, and shading dynamics that directly shape pedestrian comfort.

Conversely, microscale simulation tools such as ENVI-met, SOLWEIG, and CFD provide physically explicit representations of these processes but remain constrained by high computational cost, limited spatial coverage, and case-study specificity. As demonstrated in Sections 3.2 and 4.3, only a small subset of studies successfully bridges these scales in a manner suitable for routine planning application. Hybrid workflows combining spatial analytics with targeted simulation, machine-learning surrogates, or LCZ-informed downscaling represent a promising direction, yet they remain methodologically heterogeneous and insufficiently standardised.

This fragmentation highlights a fundamental challenge for climate-responsive planning: urban heat mitigation is inherently multi-scalar, yet current digital tools remain siloed by scale. Without explicit mechanisms to translate city-scale insights into pedestrian-scale design guidance, and vice versa, digital analyses risk remaining descriptive rather than prescriptive. Existing efforts to bridge microscale comfort processes with city-scale climate dynamics, such as LCZ-informed mesoscale modelling, urban weather generator–based pipelines, and hybrid remote sensing–simulation frameworks, demonstrate methodological potential but remain weakly embedded in everyday planning practice [67,68,89,104,105].

5.3. Limited Translation into Planning and Policy Instruments

Although a large majority of reviewed studies explicitly claim planning relevance (Figure 12), direct integration into statutory planning instruments, zoning regulations, or performance-based design codes remains rare. Digital outputs are most often presented as maps, indices, or scenario comparisons, with limited guidance on how these results should inform enforceable planning decisions such as density controls, street layout regulations, or green infrastructure requirements.

This gap reflects a persistent disconnect between analytical sophistication and institutional usability. Planning systems typically rely on simplified, interpretable metrics and thresholds, whereas digital urban climate studies frequently produce complex, multidimensional outputs without clear normative meaning. Moreover, many advanced AI-driven approaches prioritise predictive accuracy over transparency or interpretability, further limiting their acceptance in regulatory and policy contexts.

The findings of this review therefore suggest that methodological advancement alone is insufficient to drive planning uptake. Without deliberate alignment between digital outputs and planning logic, such as performance zoning, climate overlays, or heat-sensitive development controls, digital urban climate research is likely to remain influential primarily at the analytical or exploratory design level. While several studies propose simplified screening tools, clustering-based workflows, or comparative modelling ecosystems to improve planner usability, translation into formal regulatory instruments remains limited [106,107].

5.4. Climatic and Geographic Biases in Digital Urban Climate Research

The synthesis further reveals pronounced climatic and geographic biases in the literature. Hot-humid and temperate cities, particularly in East Asia and Europe, dominate digital urban climate research, while hot-arid and semi-arid regions remain underrepresented despite experiencing some of the most severe heat stress conditions globally. This imbalance constrains the generalisability of existing digital frameworks and risks reinforcing planning paradigms that are poorly suited to heat-vulnerable contexts.

These biases are two-fold. First, physical and climatic conditions are unevenly represented, with a clear dominance of temperate and hot-humid urban environments in the evidence base. Second, socio-economic and cultural contexts are also unevenly captured. Studies are disproportionately concentrated in data-rich, well-instrumented cities, whereas rapidly urbanising regions in the Global South, often characterised by informal urban morphology, limited data infrastructure, and distinct behavioural and cultural adaptation patterns, remain underrepresented. This limits the ability of current digital approaches to account for context-specific thermal perception, adaptive behaviour, and vulnerability.

In many Global South settings, studies rely disproportionately on proxy-based indicators due to data, resource, and infrastructure constraints, further marginalising human-centred comfort assessment in precisely those contexts where it is most critical. Similarly, recent large-scale studies based on remote sensing and spatial modelling continue to rely heavily on temperature proxies such as land surface temperature (LST), despite efforts to approximate human-experienced conditions through statistical conversion approaches [108]. Recent global syntheses similarly highlight the dominance of data-rich, proxy-oriented urban studies within outdoor comfort research, reinforcing these geographic asymmetries [29]. Addressing this bias requires not only transferring existing tools to underrepresented climates but also adapting methodologies to account for data scarcity, informal urban form, and culturally mediated thermal perception.

Reducing these biases will require coordinated efforts across research, policy, and funding structures. Future progress depends on the development of international and cross-regional research collaborations, increased funding support for urban climate studies in underrepresented regions, and the expansion of open-access datasets and low-cost sensing technologies. In addition, capacity-building initiatives and interdisciplinary research programmes can help localise digital methodologies and improve their applicability across diverse climatic and socio-economic contexts.

A more balanced and globally representative research landscape would directly benefit urban planners, designers, and policymakers by providing context-sensitive evidence for climate-responsive planning. It would also enhance the protection of vulnerable populations, particularly in heat-exposed regions, by supporting more equitable, inclusive, and human-centred urban adaptation strategies.

5.5. Toward Climate-Responsive and Human-Centred Digital Planning Frameworks

In this study, "human-centred digital planning frameworks" refer to integrative urban planning approaches in which digital tools and data-driven methods are explicitly designed to prioritise human thermal experience, comfort perception, and well-being as primary performance objectives. Unlike conventional digital workflows that focus predominantly on energy efficiency, morphology optimisation, or thermal exposure proxies, human-centred frameworks embed physiologically based comfort indices (e.g., PET, UTCI), behavioural adaptation, and user-oriented evaluation criteria directly into analytical, simulation, and decision-support processes.

Such frameworks are characterised by (i) the explicit integration of outdoor thermal comfort metrics into digital models, (ii) multi-scalar linkage between city-scale analytics and pedestrian-level experience, (iii) the incorporation of human perception, adaptation, and vulnerability, and (iv) the translation of digital outputs into actionable planning and design guidance. In this sense, digital tools are not only analytical instruments, but also decision-support systems oriented toward enhancing liveability, equity, and climate resilience.

Taken together, the findings of this review indicate that the next phase of digital urban climate research must move beyond tool development toward integrative, planning-oriented frameworks. Such frameworks should treat outdoor thermal comfort as a primary performance objective rather than a secondary outcome, explicitly link city-scale analytics with pedestrian-scale experience, balance predictive power with interpretability, and align outputs with planning and design decision structures.

Emerging hybrid approaches combining spatial analytics, microclimate simulation, and explainable artificial intelligence offer promising pathways toward this goal. However, their success will depend on reframing digital tools not merely as analytical engines but as decision-support systems embedded within climate-responsive urban governance. This shift toward human-centred digital planning frameworks requires rethinking digital tools as platforms that explicitly integrate environmental physics with human perception and planning decision-making processes. By foregrounding human thermal comfort as a central sustainability criterion, digital urban methods can more effectively support equitable, liveable, and climate-resilient urban development.

5.6. Operationalising Digital Urban Climate Analysis in Planning Practice

While the preceding discussion highlights the structural gaps between digital urban climate analysis and planning implementation, translating these insights into practice requires a clearer alignment between analytical outputs, spatial scales, and planning instruments.

To address this challenge, this section proposes a structured approach to operationalising digital urban climate methodologies across three complementary levels of intervention: strategic, tactical, and operational. This multi-level framework links digital tools with planning processes and provides a pathway for embedding outdoor thermal comfort within regulatory and design decision-making.

5.6.1. Strategic Level: City-Scale Planning and Policy Frameworks

At the strategic level, digital urban climate analysis supports city- and regional-scale planning decisions related to land-use allocation, climate adaptation policy, and long-term urban development. Methods in this category are predominantly based on GIS, remote sensing, and LCZ classification, enabling large-scale mapping of thermal exposure, urban heat island intensity, and climate vulnerability patterns.

Typical outputs include land surface temperature (LST) maps, SVF-derived morphological indicators, and heat-risk indices generated through remote sensing and spatial modelling approaches [100,101], which can be translated into planning instruments such as:

- heat-risk zoning and climate overlay districts, identifying priority areas for intervention,
- strategic green infrastructure planning, targeting cooling corridors, urban parks, and vegetation networks,
- climate-sensitive land-use allocation, guiding density distribution and urban expansion in heat-vulnerable areas.

At this level, thermal comfort is often represented indirectly through exposure-based indicators. However, these outputs are critical for screening, prioritisation, and policy formulation, forming the first stage in a multi-scale decision-making process.

5.6.2. Tactical Level: Neighbourhood-Scale Planning and Urban Design Strategies

At the tactical level, digital tools are applied to neighbourhoods, districts, and urban blocks to inform urban design strategies and medium-scale planning interventions. This level typically integrates geospatial analytics with simulation-based or hybrid modelling approaches, including ENVI-met, UMEP, and AI-assisted workflows.

Analytical outputs at this scale include spatially resolved fields of air temperature, mean radiant temperature (Tmrt), wind flow, and derived comfort indices such as UTCI or PET. These outputs enable the evaluation of urban form and design interventions, including:

- street orientation and canyon geometry optimisation to improve shading and ventilation,
- vegetation placement and typology to enhance evaporative cooling and reduce radiant heat exposure,
- material selection and albedo strategies to mitigate heat storage and re-radiation.

From a planning perspective, these results can be operationalised through:

- urban design guidelines and master planning frameworks, specifying acceptable ranges for building height, spacing, and street aspect ratios,
- performance-based planning criteria, where thermal comfort indicators (e.g., UTCI reduction targets or maximum Tmrt thresholds) inform design requirements,
- scenario-based evaluation tools, supporting climate-responsive urban regeneration and redevelopment projects.

At this level, the integration of microclimate processes and comfort indices becomes more explicit, enabling a transition from exposure mapping to design-oriented thermal performance assessment.

5.6.3. Operational Level: Site-Scale Design, Regulation, and Implementation

The operational level focuses on site-specific design, building-scale interventions, and the incorporation of climate-responsive criteria into regulatory frameworks such as building codes and design standards. This level relies heavily on high-resolution simulation tools, parametric modelling, and optimisation workflows, often applied within project-specific contexts.

Outputs include detailed simulations of radiation exchange, shading performance, airflow, and pedestrian-level comfort conditions, typically expressed through indices such as UTCI or PET. These outputs can be directly translated into:

- building and urban design regulations, such as minimum shading requirements, maximum allowable sky view factor (SVF), or mandatory provision of shaded pedestrian pathways,
- performance-based codes, where developments are required to meet defined thermal comfort thresholds (e.g., limiting peak UTCI values in public spaces),
- site-specific design guidelines, addressing façade design, tree canopy coverage, shading devices, and material properties.

At this level, digital tools function as decision-support systems for implementation, enabling designers and planners to evaluate and optimise thermal performance before construction. However, the widespread adoption of such approaches remains limited due to computational complexity, data requirements, and the lack of standardised regulatory frameworks.

5.6.4. Bridging Scales: Toward Integrated and Performance-Based Planning

A key implication of this multi-level framework is that no single methodological approach can address the full spectrum of planning needs. Instead, effective climate-responsive planning requires integration across scales, where outputs from one level inform decisions at another.

For example:

- city-scale heat-risk mapping can guide the selection of neighbourhoods requiring detailed microclimate simulation,
- neighbourhood-scale simulations can inform district-level design guidelines and performance targets,
- site-scale modelling can refine and validate design interventions and support compliance with performance-based regulations.

This hierarchical integration enables a shift from fragmented, scale-specific analyses toward coherent, performance-driven planning systems, in which outdoor thermal comfort is embedded as a measurable and enforceable objective.

5.6.5. Implications for Planning Practice and Policy Integration

Operationalising digital urban climate analysis ultimately requires aligning analytical outputs with institutional frameworks, regulatory instruments, and decision-making processes. This includes:

- developing standardised outdoor thermal comfort metrics and threshold ranges suitable for planning and design applications,
- improving the interpretability, transparency, and robustness of digital models to support policy adoption and stakeholder trust,
- embedding climate-responsive and comfort-driven criteria within zoning regulations, building codes, urban design guidelines, and environmental impact assessment frameworks, and

- fostering interdisciplinary collaboration between researchers, planners, designers, and policymakers to ensure applicability, scalability, and long-term implementation.

Importantly, this alignment enables the translation of digital outputs (e.g., UTCI/PET maps, microclimate simulations, AI-based predictions) into decision-support tools that can inform density regulations, street design standards, greening strategies, and heat-risk zoning at multiple planning scales.

By structuring digital methodologies across strategic (city-scale policy and zoning), tactical (district and neighbourhood planning), and operational (site-specific design and intervention) levels, the proposed framework provides a clear pathway for translating analytical advances into actionable, scalable, and human-centred planning practices.

In doing so, it directly addresses the core challenge identified throughout this review: bridging the gap between digital urban climate analysis and its effective implementation in climate-resilient, liveable, and equitable urban environments.

Together, the conceptual integration framework (Section 4.6) and the operational planning framework (Section 5.6) establish a coherent and multi-scalar pathway for embedding outdoor thermal comfort within digital, climate-responsive urban planning systems.

6. Conclusions and Future Research Directions

This review has critically examined digital and data-driven approaches to sustainable urban and land-use management through the lens of urban microclimate regulation and outdoor thermal comfort. By synthesising 78 peer-reviewed studies published between 2015 and 2025, the paper demonstrates that although digital urban methodologies have advanced rapidly in analytical sophistication, computational efficiency, and spatial coverage, the integration of human-centred thermal comfort remains limited, uneven, and methodologically fragmented.

The review reveals a dominant reliance on proxy-based indicators, most notably land surface temperature, sky view factor, and shading metrics, particularly in city- and neighbourhood-scale analyses. While such proxies provide valuable insights into spatial patterns of thermal exposure, they insufficiently represent the combined radiative, convective, and physiological processes that govern outdoor thermal perception at the pedestrian scale. Comprehensive comfort indices such as PET and UTCI are still applied primarily in microscale simulation studies or highly instrumented case studies, constraining their scalability and routine application in planning contexts. This imbalance confirms a persistent exposure- and form-centric bias within digital urban analysis frameworks and underscores the need to reposition outdoor thermal comfort as a primary performance criterion rather than a secondary or inferred outcome.

A second key finding concerns the enduring scale disconnect between digital urban analytics and lived thermal experience. Spatial data approaches, including GIS, remote sensing, and LCZ-based mapping, are effective for characterising urban heat patterns across large areas but lack the spatial and temporal resolution required to capture street-level microclimate dynamics. Conversely, high-resolution simulation tools provide detailed representations of radiation exchange, airflow, and shading but remain constrained by computational cost and limited spatial applicability. Although hybrid and AI-assisted workflows are increasingly proposed to bridge this divide, they remain methodologically heterogeneous and insufficiently embedded within planning decision-making processes. Without explicit mechanisms for scale integration, digital tools risk remaining descriptive rather than transformative.

The review also highlights a persistent implementation gap between digital climate analysis and urban planning practice. Despite frequent claims of planning relevance, few studies translate analytical outputs into actionable guidance compatible with zoning regulations, development controls, or performance-based planning instruments. This gap reflects not only institutional and governance constraints but also limited interpretability and normative clarity in many advanced digital models. For digital tools to meaningfully influence land-use decisions, their outputs must align with the simplified, enforceable logic of planning systems while retaining sensitivity to climatic processes and human experience.

Geographic and climatic biases further constrain the generalisability of current digital urban climate research. Hot-humid and temperate cities, particularly in East Asia and Europe, dominate the literature, whereas hot-arid and semi-arid regions, where heat stress poses the greatest threat to urban liveability, remain underrepresented. Moreover, studies conducted in data-scarce contexts often rely heavily on thermal proxies, reinforcing the marginalisation of human-centred comfort assessment precisely where it is most urgently needed. Addressing these imbalances is essential for developing globally relevant and equitable climate adaptation strategies.

Taken together, the findings of this review point toward a necessary methodological shift in digital urban research. Future work should prioritise the explicit integration of outdoor thermal comfort into digital planning workflows by combining spatial analytics, microclimate simulation, and explainable artificial intelligence within coherent, multi-scalar frameworks. Such approaches should aim not only to improve predictive performance but also to enhance interpretability, support scenario-based decision-making, and align outputs with planning and design instruments. Greater attention is also required to culturally and climatically specific adaptive behaviours, alongside validation strategies that integrate instrumental measurements with human perception.

Building on these findings, future research must move beyond conceptual development toward methodologically robust and operationally grounded frameworks. This requires the development of standardised datasets and interoperable data infrastructures that enable the consistent comparison of urban microclimate and outdoor thermal comfort across diverse climatic and geographic contexts. In parallel, cross-scale validation methodologies are needed to systematically link city-scale analytics with pedestrian-scale thermal experience, ensuring that digital outputs remain both physically accurate and planning-relevant.

Further advances should prioritise hybrid and AI-driven approaches that integrate spatial analytics, microclimate simulation, and data-centric modelling within unified workflows. Such approaches offer strong potential to enhance scalability, computational efficiency, and interpretability, while supporting real-time and scenario-based planning applications. However, their development must be accompanied by rigorous validation, transparency, and transferability across climatic, cultural, and socio-economic contexts.

Crucially, future research must also focus on embedding digital outputs into planning and policy frameworks, including zoning regulations, urban design guidelines, and climate adaptation strategies. This entails translating thermal comfort indices and microclimate metrics into actionable thresholds, performance indicators, and decision-support tools that can be directly applied in planning practice.

By foregrounding outdoor thermal comfort as a central indicator of urban sustainability, this review provides a climate-responsive and human-centred synthesis of contemporary digital urban methodologies. It demonstrates that the true potential of data-driven approaches lies not in technical optimisation alone, but in their capacity to support liveable, equitable, and climate-resilient urban environments, particularly in heat-vulnerable regions facing the most urgent adaptation challenges.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18083710/s1, Supplementary Table S1 provides the complete structured dataset of the reviewed studies (n = 78), including methodological attributes, spatial scales, variables, comfort metrics, and planning relevance. Supplementary Table S2 presents the coding framework and criteria used for assessing planning relevance across the reviewed studies.

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