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Beyond the Green Shade: An Analytical Evaluation of Outdoor Thermal Comfort Research in Hot/cold-Arid Urban Environments

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A B S T R A C T

The rapid growth of urban populations has placed increasing pressure on the built environment, resulting in a reduction of outdoor spaces and a decline in environmental quality. These challenges have intensified the need for outdoor thermal comfort studies to better address the consequences of urbanization and climate change. Objectives: This study aims to critically review the recent literature (from the last four years) on outdoor thermal comfort in urban environments. It examines both micro-scale (qualitative) and macro-scale (quantitative) approaches, identifies key research gaps, and suggests future research directions, with emphasis on standardizing thermal indices and integrating psychological dimensions of comfort. A systematic review was conducted using major academic databases. After applying inclusion and exclusion criteria through title, abstract, and full-text screening, 50 relevant peer-reviewed articles were selected. These were analyzed based on scope, methodologies, indices used, and geographical distribution. The review identified a lack of consensus on thermal comfort indices across climate zones, and limited integration of psychological and adaptive factors. Moreover, research efforts are unevenly distributed, with some regions receiving disproportionate attention while others remain understudied. There is a critical need for standardizing thermal comfort metrics and defining climate-specific neutral value ranges. Future research should adopt interdisciplinary approaches, combining environmental and psychological insights to improve understanding and design of thermally comfortable urban spaces. This review serves as a reference for academics, designers, and planners seeking to enhance thermal comfort in increasingly dense urban environments. The review underscores that standardized cooling strategies without contextual adaptation to local climate, urban morphology, and materials show limited efficacy, urging region-specific solutions.

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Introduction

Outdoor Thermal Comfort (OTC) has become a central concern in urban climate research, particularly in the face of intensifying climate change, rapid urbanization, and increasing heat stress in cities located in hot-arid and cold-arid regions. Arid and semi-arid regions cover approximately 40% of the global land area, supporting about two billion people. These areas have seen increased warming and droughts, which exacerbate the risk of desertification and impact local ecosystems and populations, especially in the global drylands (Li et al., 2020). The compounded effects of rising Land Surface Temperatures (LST) and the Urban Heat Island (UHI) phenomenon have prompted planners and researchers to adopt simulation-based approaches to evaluate microclimatic conditions and propose adaptive design strategies (Zhu et al., 2024; Lai et al., 2020).

Simulation tools such as ENVI-met, RayMan, and Computational Fluid Dynamics (CFD) are widely employed to assess thermal indices including Physiological Equivalent Temperature (PET), Universal Thermal Climate Index (UTCI), and Predicted Mean Vote (PMV). These tools provide quantitative insights into how urban morphology, surface materials, and vegetation influence thermal perception. However, most of these indices were originally developed under temperate or humid climatic assumptions, raising concerns about their applicability in arid environments (Elraouf et al., 2022; Gomaa et al., 2024).

Recent studies have explored OTC across various urban typologies—residential buildings (Mirzabeigi & Razkenari, 2022; Liu et al., 2022), urban districts (Ioannidis et al., 2024; Yang & Li, 2020), parks (Behzad & Guilandoust, 2024), university campuses (Brozovsky et al., 2021), and pedestrian zones (Mokhtar & Reinhart, 2023). These investigations span diverse climatic zones and often focus on physical parameters such as height-to-width ratio (H/W), sky view factor (SVF), and orientation (Ali-Toudert & Mayer, 2006; Galal et al., 2020).

Despite the growing body of literature, several methodological and contextual gaps persist. Many studies rely on imported solutions—vegetation-based cooling, artificial shading, and high-albedo surfaces—without adequately considering ecological costs, water scarcity, or long-term feasibility in arid settings (Xu et al., 2019). In contrast, vernacular urban forms—narrow alleys (sabats), inward-facing courtyards, and thick adobe walls—offer passive cooling strategies rooted in centuries of climatic adaptation, yet remain underrepresented in simulation research.

Moreover, discrepancies between standard comfort thresholds and actual thermal perception in arid climates suggest that existing indices may require recalibration to account for behavioral and physiological adaptations, such as clothing choices and wind exposure (Bacha et al., 2024). Behavioral practices—midday activity avoidance, flexible attire, and cultural expectations—play a significant role in shaping outdoor comfort but are often excluded from simulation frameworks (Aljawabra & Nikolopoulou, 2018).

Another overlooked dimension is the integration of remote sensing tools like MODIS, Landsat, and Sentinel-2, which offer valuable data on LST, vegetation indices (NDVI), and built-up density (NDBI) (Onačillová et al., 2022; Almeida et al., 2025). These datasets can enhance the spatial and temporal resolution of OTC assessments but are rarely used systematically.

This review critically examines simulation-based OTC research in arid urban environments by analyzing 50 peer-reviewed studies published over the past four years. It highlights methodological limitations, ecological oversights, and cultural blind spots, advocating for a contextualized modeling approach that integrates remote sensing, behavioral adaptation, and vernacular design logic. The review spans microscale to macroscale studies and includes only those addressing both subjective and objective thermal comfort using validated indices.

The paper is organized as follows. The research methodology is described in Section 2. In Section 3, the paper delves into a comprehensive analysis of the results obtained, along with an in-depth discussion surrounding those findings. Following this detailed exploration, Section 4 is dedicated to presenting the final conclusion of the paper, summarizing the key points and implications of the research conducted.

Methodology

This study adopts a systematic review methodology, emphasizing thermal comfort assessments specifically in hot/ cold-arid environments. Building on a refined research framework, we prioritized simulation-based studies that focused on (a) cities within hot/ cold-arid climatic zones, (b) traditional urban typologies (e.g., courtyards, narrow alleys, sabats), and (c) the application or critique of standardized thermal indices (PET, UTCI, PMV) under dryland conditions.

Special attention was given to studies that considered behavioral adaptation, cultural practices, and ecological limitations of vegetation-based cooling. We also included research incorporating remote sensing datasets (LST, NDVI, NDBI) into OTC analysis. The selection criteria were thus adjusted to capture more context-sensitive approaches and interdisciplinary perspectives that reflect dryland urbanism.

The foundational research question addressed in this research are (1) What is the relationship between the studied city's latitude and the thermal comfort index? (2) How does the software used relate to OTC across the studied years? (3) To what extent changes in urban design and vegetation in various urban spaces (e.g., streets, sidewalks, parks) enhance thermal pleasure and thermal comfort? (4) What is the relationship between the city's physical components, comfort indicators, and microclimatic parameters?

Search procedure

Based on the narrative literature review, we developed four research questions aimed at advancing the field of dynamic OTC. Below, we outline these questions, summarize current research, identify gaps, and propose pathways for progress. Our findings emphasize the importance of considering holistic exposure to environmental stimuli alongside physiological parameters and subjective judgments. We also address how other sensory experiences affect thermal comfort, the impact of urban forms on thermal pleasure, and the necessity of integrating socio-economic and cultural dimensions to enhance existing OTC models.

The review is based on 50 research papers. The following procedure was followed to select appropriate studies for the review. As per the study by Falagas et al. (Falagas et al., 2008), commonly used databases are Google Scholar, and ResearchGate. These databases were searched in this review. Publishers' websites such as Taylor and Francis, MDPI, and Springer were also searched. The Keywords used were "thermal comfort", "Urban spaces Simulation", "urban thermal comfort", and "outdoor thermal comfort".

The search resulted in original journal articles, and review articles. Figure 1 shows the broader steps involved in the search, filtration, and output in terms of the number of articles. Screening and filtration were performed manually by reading the titles and abstracts to check whether the articles are in the scope of the review. The selection criteria are based on the limitation of this review: 1) The studies conducted at outdoor open spaces, 2) Studies conducted user surveys, 3) Addressed the issues of outdoor open spaces within the urban limit, 4) Considered the interaction of the user climate-built environment. 5) Articles published in the past 5 years. 50 articles were finally selected for the review (Table 1).

Table 1. Studies selected for the review.

NO.	RESEARCHERS	YEAR	PUBLISHED IN JOURNAL	JOURNAL RANKING	CITIES	COUNTRY
1	(Teshnehdel et al., 2020)	2020	Building and Environment	Q1	Tabriz	Iran
2	(Yang & Li, 2020)	2020	Environmental Technology & Innovation	Q1	Xiantao city	China
3	(Natanian et al., 2020)	2020	Energy & Buildings	Q2	Basel	Switzerland
4	(Das & Das, 2020)	2020	Urban Climate	Q1	Sriniketa n-Santinike tan Panning Area	India
5	(Das et al., 2020)	2020	Sustainable cities and society	Q1	Sriniketa n-Santinike tan Planning Area	India
6	(J. Brozovsky et al., 2021)	2021	Energy & Buildings	Q2	Trondhei m	Norway
7	(Lim & Ooka, 2021)	2021	Energies	Q3	Tokyo	Japan
8	(Johannes Brozovsky et al., 2021)	2021	Building and Environment	Q1	Trondhei m	Norway
9	(Chen et al., 2021)	2021	Sustainable cities and society	Q1	Guangzh ou	China
10	(Aghamolaei et al., 2021)	2021	Energy and Buildings	Q2	Tehran	Iran
11	(Detommaso et al., 2021)	2021	Urban Climate	Q1	Catania	
12	(Manavvi & Rajasekar, 2021)	2021	Building and Environment	Q1	New Delhi	India
13	(Kaseb & Rahbar, 2022)	2022	Sustainable cities and society	Q1	Not Mention	Not Mention
14	(Mirzabeigi & Razkenari, 2022)	2022	Sustainable cities and society	Q1	Syracuse	USA
15	(Shah et al., 2022)	2022	Alexandria Engineering Journal	Q1	Gwalior	India
16	(Yao et al., 2022)	2022	Sustainable cities and society	Q1	Tibetan plateau	China
17	(Athamena, 2022)	2022	Urban Climate	Q1	Lyon	France
18	(Liu et al., 2022)	2022	Building and Environment	Q1	Singapor e	Singapore
19	(Abd Elraouf et al., 2022)	2022	Building and Environment	Q1	Port Said	Egypt
20	(Zhang et al., 2022)	2022	Building and Environment	Q1	Tianjin	China
21	(Yuan et al., 2022)	2022	Building and Environment	Q1	Osaka	Japan
22	(Fallahpour et al., 2022)	2022	Building and Environment	Q1	Los Angeles	USA
23	(S & Rajasekar, 2022)	2022	Building and Environment	Q1	Chandiga rh	India
24	(Teshnehdel et al., 2022)	2022	Land	Q2	Tabriz	Iran
25	(Back et al., 2023)	2023	Science of the Total Environment	Q1	Innsbruc k	Austria
26	(Q. Wu et al., 2023)	2023	Atmosphere	Q3	Fuzhou	China

27	(Perišić et al., 2023)	2023	Applied science	Q2	Novi Sad	Serbia
28	(Izadyar et al., 2023)	2023	Journal of Building Performance Simulation	Q3	Brisbane	Australia
29	(Chockalingam et al., 2023)	2023	Atmosphere	Q3	Basel Sperrstrasse	Switzerland
30	(Yuan et al., 2023)	2023	Heliyon	Q2	Toyohashi	Japan
31	(Lai et al., 2023)	2023	Urban Climate	Q1	Osaka	Japan
32	(Haeri et al., 2023)	2023	Urban Climate	Q1	Kuala Lumpur	Malaysia
33	(X. Zheng et al., 2023)	2023	Building and Environment	Q1	Haikou	China
34	(Mokhtar & Reinhart, 2023)	2023	Building and Environment	Q1	San Francisco	USA
35	(Sun et al., 2023)	2023	Energy and Buildings	Q2	Tianjin	China
36	(Kridakorn Na Ayutthaya et al., 2023)	2023	Energy reports	Q2	Thailand	Thailand
37	(Qiu et al., 2024)	2024	Atmosphere	Q3	Jinjiang	China
38	(Ioannidis et al., 2024)	2024	Atmosphere	Q3	Augsburg	Germany
39	(K. L. Wu & Shan, 2024)	2024	Atmosphere	Q3	Zhumadian	China
40	(Stasi et al., 2024)	2024	Building and Environment	Q1	Mumbai	India
41	(Hågbo & Giljarhus, 2024)	2024	Building and Environment	Q1	Bryne	Norway
42	(J. Wu et al., 2024)	2024	Journal of Building Engineering	Q1	Nanjing	China
43	(Pompei et al., 2024)	2024	Energy and Buildings	Q2	Rome	Italy
44	(Mahdavinejad et al., 2024)	2024	Urban Climate	Q1	Bushehr	Iran
45	(Banerjee et al., 2024)	2024	Sustainable cities and society	Q1	Singapore	Singapore
46	(Behzad & Guilandoust, 2024)	2024	Sustainable cities and society	Q1	Isfahan	Iran
47	(Kotharkar & Dongarsane, 2024)	2024	Building and Environment	Q1	Nagpur	India
48	(Su et al., 2024)	2024	Sustainable cities and society	Q1	Dalian	China
49	(Ben Ratmia et al., 2024)	2024	sustainability	Q3	Biskra	Algeria
50	(Y. Zheng et al., 2024)	2024	Land	Q2	Shenzhen	China

Data extraction and classification

The final selected studies were gathered in Mendeley, a referencing program for organizing articles. Primary analysis was conducted using Microsoft Excel, where data were organized into tables to prevent loss of valuable information. Articles were filtered based on their Journal Citation Reports (JCR) ranking, and those without a ranking were excluded. Full-text availability was then verified, removing any articles without accessible full texts. The entire process was conducted manually, as the number of articles was limited to 50(figure 1).

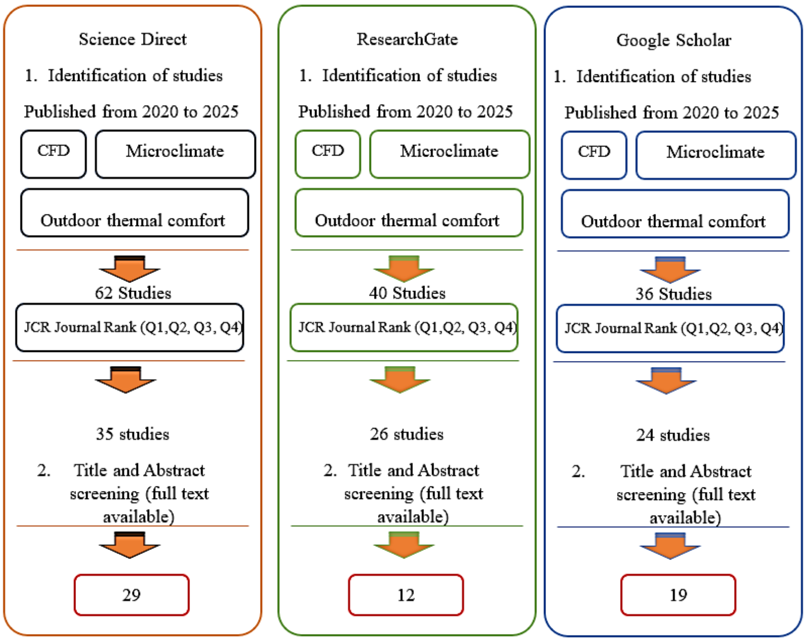


Figure 1. Literature search process.

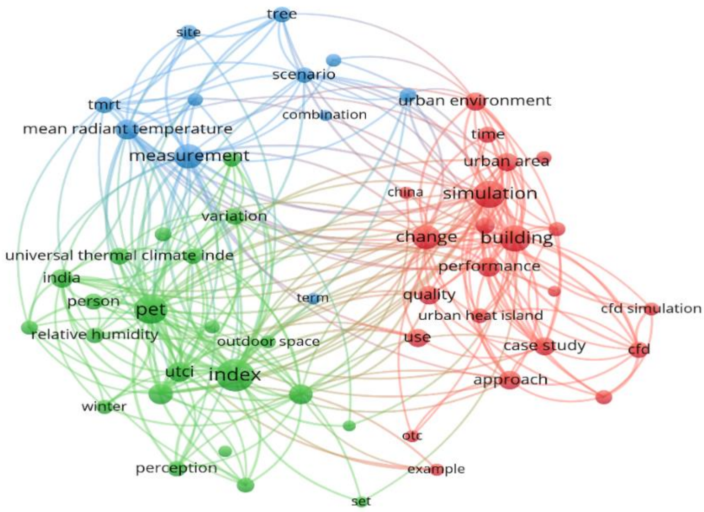


Figure 2. Keyword Co-occurrence Network in Outdoor Thermal Comfort Studies (2020–2025)

Figure 2.categorizes key terminologies into physical-environmental metrics (blue), contextual and behavioral variables (green), and urban design and simulation concepts (red). Dense interconnections highlight the interdisciplinary nature of thermal comfort research, requiring integration of climate data with socio-cultural and perceptual factors. Achieving sustainable outdoor thermal comfort in arid urban areas necessitates environmental engineering, responsive urban design, and culturally attuned methodologies.

Results and discussion

What is the relationship between the studied cities' latitude and the thermal comfort index?

The analysis of the selected 50 studies reveals significant geographic and conceptual imbalances. While the majority of simulation studies used PET, UTCI, and PMV, few calibrated these indices for hot/cold-arid conditions. In cities like Tehran, Cairo, and Mashhad, studies indicate that thermal neutrality under shaded conditions occurs at PET values exceeding 34 °C—far beyond comfort thresholds defined for temperate climates. This discrepancy highlights the inadequacy of unadjusted thermal indices in arid zones.

Only a small subset of research engaged with vernacular forms (e.g., courtyards, adobe walls, shaded passageways), despite their proven effectiveness in heat mitigation. Similarly, while many studies promoted trees and green infrastructure as universal solutions, few considered the ecological feasibility of such strategies in water-scarce environments.

Behavioral adaptation remains significantly underrepresented: practices such as clothing adjustment, time-based outdoor activity scheduling, or socio-cultural comfort norms were largely omitted from simulation frameworks. Moreover, less than 10% of studies integrated satellite-based indicators (e.g., LST, NDVI) into urban comfort assessments, missing an opportunity to link large-scale environmental change to microclimatic outcomes.
A comparative synthesis of traditional versus modern shading interventions is notably absent, despite evidence that traditional morphology may offer superior performance with lower environmental costs.

Table 2. Thermal Comfort Characteristics by Latitude Zone: Stress Patterns and Key Moderators

Latitude Zone	Thermal Comfort Characteristics	Dominant Stress	Examples	Key Moderating Factors	Number of researches(%)
Low (0°–23.5°) (Tropical/Subtropical)	Consistently high solar radiation → elevated temperatures & humidity. Minimal seasonal variation.	**Chronic heat stress** (UTCI/PET often >26°C)	Singapore, Mumbai	Humidity, urbanization (UHI effect), ocean currents	37%
Mid (30°–60°) (Temperate)	Strong seasonal swings → hot summers, cold winters. Bimodal discomfort patterns.	**Dual stress**: Summer heat & winter cold	New York, Beijing	Continentality, altitude, UHI, wind patterns	55%
High (>60°) (Subarctic/Polar)	Low solar angle → long, extreme winters; short cool summers. Limited daylight in winter.	**Prolonged cold stress** (UTCI/PET often <9°C)	Helsinki, Reykjavik	Maritime influence, snow cover, wind chill	8%

Table 2 showed that the relationship between a city's latitude and its thermal comfort index is primarily direct and deterministic, as latitude controls solar radiation intensity and seasonal temperature patterns. At low latitudes (near the equator), intense and direct solar radiation causes high temperatures and humidity, leading to chronic heat stress (e.g., high UTCI or PET index values). Conversely, at high latitudes (near the poles), oblique solar radiation and prolonged winters create dominant cold stress. Although latitude shapes the climatic baseline of a city, local factors can modify or even alter this relationship. Elevation (e.g., mountainous cities), proximity to the sea (moderating effects of humidity and wind), the urban heat island phenomenon (temperature rise in dense areas), and air humidity (intensifying equatorial heat or humid winter cold) can transform the predicted patterns based on latitude. Thus, in practice, thermal comfort results from combining latitude as a macro-scale factor and local microclimatic factors.

Cities within tropical and subtropical latitudes, such as Singapore and Mumbai, are characterized by persistently high solar radiation, elevated humidity, and minimal seasonal variation. These conditions result in chronic heat stress, with Universal Thermal Climate Index (UTCI) and Physiological Equivalent Temperature (PET) values frequently exceeding 26°C. To mitigate thermal discomfort, urban design must prioritize passive cooling strategies. Key interventions include the integration of extensive shading through vegetation and architectural elements, utilization of high-albedo materials to reduce surface heat absorption, and the creation of ventilation corridors to enhance airflow. Additionally, strategies to counteract the Urban Heat Island (UHI) effect—such as green roofs and permeable surfaces—are essential for regulating microclimates.

Temperate cities (Mid Latitude Zone (30°–60°): Temperate Regions) like New York and Beijing experience pronounced seasonal variation, with hot summers and cold winters producing bimodal patterns of thermal discomfort. This dual stress condition necessitates adaptive design approaches capable of responding to both heat and cold extremes. Notably, 55% of thermal comfort research is concentrated in this latitude zone, reflecting its climatic complexity and urban density. Urban spaces should be designed for seasonal flexibility. Deciduous vegetation can provide shade in summer while allowing solar access in winter. Materials with moderate thermal mass help buffer temperature fluctuations. Semi-enclosed public spaces equipped with localized heating and ventilation systems can extend outdoor usability across seasons. Passive solar design and natural cooling techniques should be integrated to optimize energy efficiency and comfort.

Cities such as Helsinki and Reykjavik in High Latitude Zone (>60°), located in high-latitude zones, are subject to prolonged cold stress due to low solar angles, extended winters, and limited daylight. UTCI and PET values often fall below 9°C, and only 8% of research has focused on these regions, indicating a gap in climate-specific urban design literature. Design strategies must emphasize thermal retention and psychological comfort. Built environments should maximize solar gain through orientation and form, and incorporate high thermal mass and insulation to reduce heat loss. Localized heating elements—such as heated seating and radiant surfaces—can enhance outdoor usability. Wind protection through urban morphology and the use of warm-colored materials and lighting can further improve perceived comfort and encourage year-round engagement with public spaces.

The geographic distribution of studies shows that from 49 single-studied sites, research is mainly focused on three countries (Figures 3): China (24.49%), India (14.28%), and Iran (10.2%). The global distribution of thermal comfort study sites, as illustrated by the red markers on the map, reveals a pronounced concentration in mid-latitude regions (30°–60°), particularly across North America, Europe, and East Asia. This pattern reflects the climatic complexity of temperate zones, where both summer heat and winter cold necessitate comprehensive investigations into outdoor thermal comfort (OTC). In contrast, tropical and subtropical regions (0°–23.5°), despite experiencing chronic heat stress, are moderately represented, suggesting a research gap in areas most vulnerable to elevated temperatures and humidity. High-latitude zones (>60°), including subarctic and polar regions, show sparse coverage, likely due to their extreme cold conditions and lower urban densities. Notably, regions such as Africa, the Middle East, and parts of Central Asia remain underrepresented, highlighting the need for more geographically inclusive research.

Expanding empirical and simulation-based studies into these areas is essential for developing context-specific urban design strategies and enhancing climate resilience in rapidly urbanizing and climate-sensitive regions.

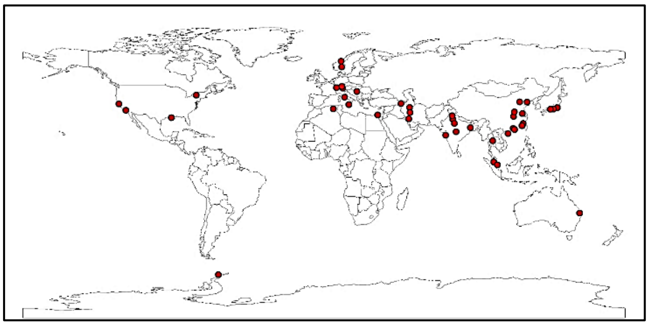


Figure 3. Geographical distribution of study sites.

A review of previous studies provides insights into the latitudinal ranges examined. The research focused on classifying latitudes, identifying those above 60 degrees as High latitude, which account for approximately 8% of the studies, indicating sparse representation in this category. In contrast, the Middle latitude group, spanning between 30 to 60 degrees, encompasses around 55% of the studies, reflecting significant interest in this range. Lastly, about 37% of studies fall within the Low latitude classification, below 30 degrees. This distribution shows varying research focus across latitudinal ranges, with a marked emphasis on middle latitudes compared to high and low latitudes.

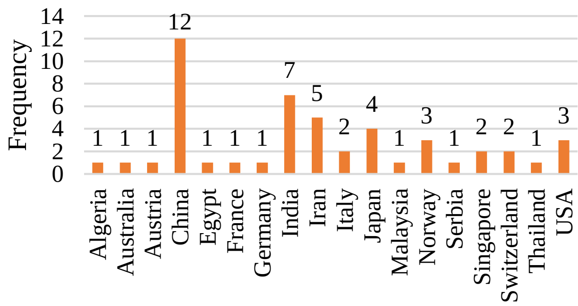


Figure 4. Geographic distribution of study sites—country of study site

According to the Köppen climate classification, two of the selected case study locations—Ismailia (Egypt) and Biskra (Algeria)—fall within the hot desert climate (BWh) zone. This climate is typified by extremely high temperatures, particularly in the summer months, and minimal annual precipitation. Such environments are predominantly found in arid desert regions, where the combination of intense solar radiation, lack of vegetation, and limited humidity poses significant challenges to achieving outdoor thermal comfort.

Additionally, five of the selected cities are categorized under semi-arid or cold desert climates, including classifications BSh, BSk, and BWk. These regions are characterized by low annual rainfall and varying temperature ranges, depending on latitude and altitude. For instance, Isfahan in Iran exhibits a cold desert climate (BWk), while Tabriz shows cold semi-arid conditions (BSk). Cities like Delhi and Chandigarh in India experience warm semi-arid climates (BSh). Bangkok, although typically tropical, demonstrates semi-arid tendencies during its dry season. These climatic zones are particularly relevant when evaluating heat mitigation strategies and assessing the potential for climate-responsive urban design. (Figure 5)

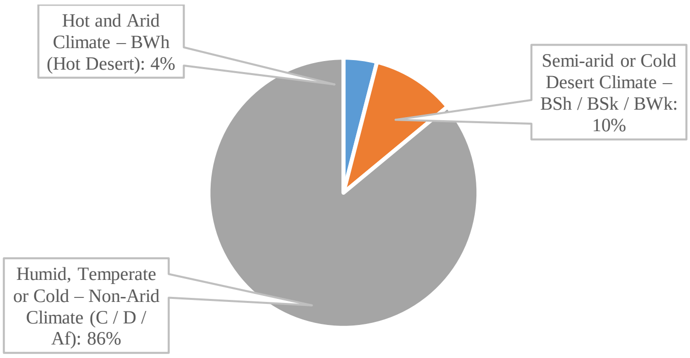


Figure 5. Distribution of Köppen Climate Types among the Studied Locations

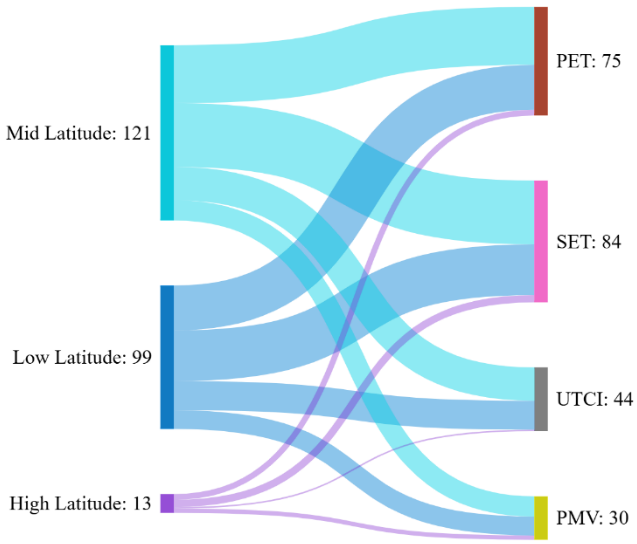
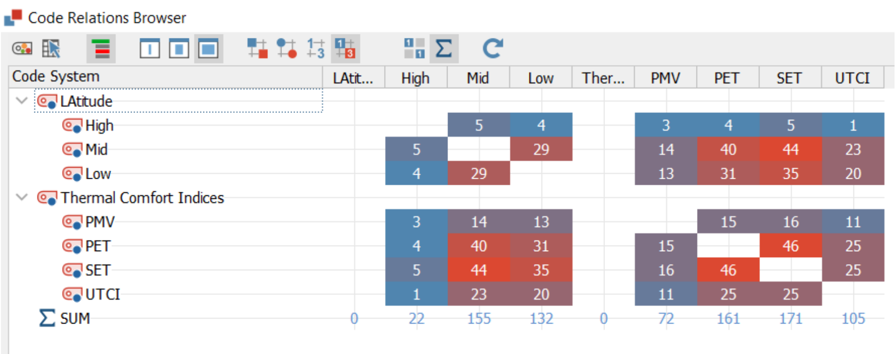


Figure 6. Relation between the studied city's latitude and the thermal comfort index

Figure 6 showed that PET and SET are central to the network, linking nearly all categories (Mid, Low, UTCI, PMV). PET, with its numerous connections and strong linkage, likely serves as a key variable in this study. The Mid and Low categories primarily classify thermal conditions and connect to the indices rather than each other. The association between UTCI, PET, and SET suggests their frequent examination within a shared context, such as analyzing a specific climatic condition or scenario.


Code Relations Browser

Code System	LAtit...	High	Mid	Low	Ther...	PMV	PET	SET	UTCI
LAtitude									
High			5	4		3	4	5	1
Mid		5		29		14	40	44	23
Low		4	29			13	31	35	20
Thermal Comfort Indices									
PMV		3	14	13			15	16	11
PET		4	40	31		15		46	25
SET		5	44	35		16	46		25
UTCI		1	23	20		11	25	25	
SUM	0	22	155	132	0	72	161	171	105

Figure 7. Co-occurrence Patterns of Latitude Zones and Theraml comfort indicies in Urban Thermal Comfort Studies

The co-occurrence matrix illustrates the relationship between latitude zones and the thermal comfort indices applied in urban climate studies. The results indicate that mid-latitude regions dominate research activity, showing the highest co-occurrence counts across all four indices, with particularly strong associations with SET (46 cases) and PET (40 cases). Low-latitude regions follow closely, especially in their application of SET (35 cases) and PET (31 cases), reflecting the importance of these indices in hotter climates where human thermal perception is highly sensitive to microclimatic variations. In contrast, high-latitude regions exhibit considerably lower engagement, with a maximum of only 5 cases for SET, which may be due to the reduced urgency of outdoor thermal comfort challenges in cold climates. Among the indices, SET emerges as the most frequently used overall (171 cases), followed by PET (161 cases), UTCI (105 cases), and PMV (72 cases), suggesting a preference for dynamic and physiologically-based models over simpler predictive indices. This pattern underscores the combined influence of climatic conditions and methodological preferences on the selection of thermal comfort assessment tools in different geographic contexts. (figure.7)

How does the software used relate to OTC across the studied years?

The research data shows that many software options exist for assessing thermal comfort in urban spaces. The reviewed studies include 7 articles utilizing CFD software, 13 utilizing ENVI-met, and 8 using OpenFOAM and Ansys Fluent for simulations. However, the use of Ladybug, Butterfly, Galapagos, COMSOL, and WindPerfect DX for thermal comfort investigations is limited. The figure 8 shows the frequency of software usage.

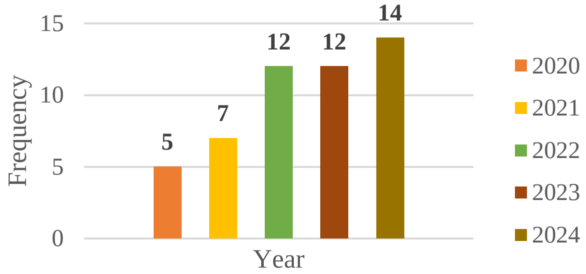


Figure 8. Article frequency chart by year

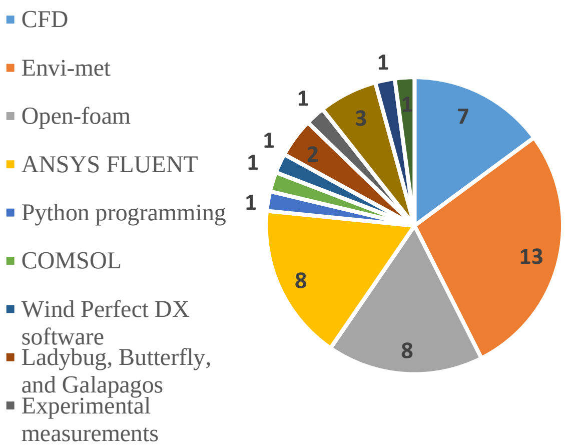


Figure 9. Software usage in publications.

Crosstab

	2020	2021	2022	2023	2024	Total
COMSOL					7	7
Butterfly			7	2		9
Ladybug	7	3	10	6	2	28
Genetic algorithm		6	28	11	5	50
Envi_met	2	26	3		7	38
CFD	17	230	264	439	409	1359
Σ SUM	26	265	312	458	430	1491
# N = Documents	5 (10.0%)	7 (14.0%)	12 (24.0%)	12 (24.0%)	14 (28.0%)	50 (100.0%)

Figure 10. crosstab table presents the trend of using different simulation tools and analytical methods in studies exported from MAXQDA2020

Figure 10 shows that: CFD (Computational Fluid Dynamics) is by far the most widely used tool, increasing from 17 instances in 2020 to a peak of 439 in 2023, and maintaining a high level with 409 in 2024. This clearly indicates the establishment of CFD as the dominant method for airflow and environmental condition analysis. Envi-met, with a total of 38 uses over five years, ranks second after CFD. Its highest usage occurred in 2021 (26 instances), followed by a decline in subsequent years. This drop may be due to the substitution of Envi-met with CFD in more complex projects or its integration as a supplementary tool. Genetic algorithm, with 50 uses, shows a relatively stable trend with gradual growth until 2022, being mainly applied as an optimization approach in combination with simulation tools. Ladybug (28 uses) and Butterfly (9 uses) have smaller shares compared to the above tools, though Ladybug shows more activity in 2022 and 2023. This suggests a growing adoption of Rhino/Grasshopper plugins for climatic and solar radiation analysis. COMSOL has the lowest use (7 instances) during this period, indicating that despite its multiphysics capabilities, it is less applied in the examined research context.

Overall, the results reveal that CFD has firmly established itself as the primary microscale analysis method in recent studies, while tools like Envi-met and Ladybug serve complementary roles. Genetic algorithms are primarily used for scenario optimization. The upward trend in tool usage until 2023, followed by a slight drop in 2024, may reflect market saturation or a shift in research approaches.

Code Relations Browser

Code System	LAtit...	High	Mid	Low	soft...	CO...	Butt...	Lady...	Gen...	Envi...	CFD
LAtitude											
High			5	4					2	1	5
Mid		5		29		1	3	9	8	9	40
Low		4	29				2	7	6	6	30
softwares											
COMSOL			1						1		1
Butterfly			3	2				1	2		3
Ladybug			9	7			1		2	2	9
Genetic algorithm		2	8	6		1	2	2			9
Envi_met		1	9	6				2			9
CFD		5	40	30		1	3	9	9	9	
Σ SUM	0	17	104	84	0	3	11	30	30	27	106

Figure 11. Co-occurrence Patterns of Latitude Zones and Simulation Software in Urban Thermal Comfort Studies

Figure 11. showed the co-occurrence analysis that CFD simulation is the most frequently used modeling tool in urban thermal comfort studies, with the highest prevalence in mid-latitude (40 cases) and low-latitude (30 cases) regions, indicating its dominant role in this field. In contrast, Ladybug and Envi_met, while applied across all latitude zones, appear less frequently than CFD and are primarily used as complementary tools for microclimatic analysis. Genetic algorithms and Butterfly are mainly observed in mid- and low-latitude studies, suggesting a greater focus on optimization approaches in warmer and temperate climates. Moreover, the significantly lower volume of research in high-latitude areas may be attributed to data limitations or the relatively

lower importance of thermal comfort issues in cold regions. Overall, the pattern highlights that the choice of software and modeling approach is strongly influenced by climatic conditions and the geographical location of the study area.

Although simulation tools such as CFD and ENVI-met dominate the reviewed literature, only a limited number of studies validated their models against empirical field measurements. The absence of systematic calibration using on-site climatic data (e.g., temperature, humidity, wind speed) reduces the reliability of simulation outputs, particularly in arid and semi-arid climates where soil moisture and vegetation parameters differ significantly from temperate defaults.

Future research should prioritize hybrid approaches that combine high-resolution simulation with field monitoring campaigns. This integration not only improves model accuracy but also helps capture socio-behavioral adaptations observed in real urban environments. Examples include coupling ENVI-met simulations with microclimatic stations, or validating CFD airflow patterns using drone-based thermal imaging.

To what extent changes in urban design and vegetation in various urban spaces (e.g., streets, sidewalks, parks) enhance thermal pleasure and thermal comfort?

Comparative study in different urban areas, for example Teshnehdel et al. (2020) in Iran (Residential neighborhoods in Tabriz) and Das & Das (2020) in India (Urban areas and the impact of various parameters like vegetation cover, building types, and urban orientation) showed that significant differences in thermal conditions and improvement strategies in different urban areas and emphasize the importance of appropriate design and local strategies to enhance thermal comfort.

A notable shortcoming in current OTC research is the limited application of future climate projections. Integrating climate change scenarios—such as CMIP6 datasets or downscaled regional climate models—into urban thermal comfort modeling would allow for proactive adaptation strategies. Only a handful of studies in the reviewed corpus attempted to project comfort conditions under +1.5°C or +2°C warming scenarios, leaving significant uncertainty regarding the resilience of current design solutions.

Table 3. Frequency chart of Real Urban Case study or Simplified Model

Case Study	Real Urban Case Study	Simplified Model
Number of researches	34	16
%	68%	32%

Table 4. Frequency chart of Case study type

Case Study	Number of researches	Resource	%	Strategies for Thermal Comfort Enhancement
Street	6	(Ben Ratmia et al., 2024; Haeri et al., 2023; Kridakorn Na Ayutthaya et al., 2023; Shah et al., 2022; X. Zheng et al., 2023)	12%	Shading devices, vegetation cover, reflective pavements, wind channeling
Pedestrian	1	(Mokhtar & Reinhart, 2023)	2%	Canopy shading, evaporative cooling, vegetation corridors
City squares	1	(Su et al., 2024)	2%	Urban greening, water features, shading pavilions
Building material/ Form	3	(Lai et al., 2023; Sun et al., 2023; Yuan et al., 2023)	6%	High-albedo materials, thermal mass optimization, façade greening
Traditional courtyard	1	(Mahdavinejad et al., 2024)	2%	Passive cooling, vegetation shading, water ponds

Park	3	(Behzad & Guilandoust, 2024; Manavvi & Rajasekar, 2021; Teshnehdel et al., 2022)	6%	Tree planting, green surfaces, water bodies
Residential area	15	(Abd Elraouf et al., 2022; Athamena, 2022; Banerjee et al., 2024; Chen et al., 2021; Detommaso et al., 2021; Fallahpour et al., 2022; Izadyar et al., 2023; Kaseb & Rahbar, 2022; Liu et al., 2022; Mirzabeigi & Razkenari, 2022; Natanian et al., 2020; Teshnehdel et al., 2020; K. L. Wu & Shan, 2024; Yuan et al., 2022)	3%	Urban greenery, building orientation, permeable surfaces, shading
Highrise building	1	(Stasi et al., 2024)	2%	Vertical greening, reflective roofs, cross-ventilation design
University campus	2	(J. Brozovsky et al., 2021; Johannes Brozovsky et al., 2021)	4%	Tree shading, cool pavements, courtyard cooling
LCZ (Local Climate Zone)	3	(Das & Das, 2020; Kotharkar & Dongarsane, 2024)	6%	Vegetation increase, reflective materials, compact design
Urban Blocks	4	(Chockalingam et al., 2023; Perišić et al., 2023; Pompei et al., 2024; Q. Wu et al., 2023)	8%	Building orientation, street canyon ventilation, green roofs
Urban district	7	(Aghamolaei et al., 2021; Back et al., 2023; Hågbo & Giljarhus, 2024; Ioannidis et al., 2024; Qiu et al., 2024; Yang & Li, 2020; Y. Zheng et al., 2024)	14%	Mixed-use planning, large-scale greening, ventilation corridors
Urban Furniture (air Condition)	1	(J. Wu et al., 2024)	2%	Cooling stations, misting devices, shaded seating
Stadium	1	(Zhang et al., 2022)	2%	Retractable roofs, evaporative cooling, reflective materials
Plaza/ Waterfront	1	(S & Rajasekar, 2022)	2%	Water features, tree shading, pergolas

Thermal Mitigation Strategies for Dry Urban Environments

To effectively mitigate thermal stress in hot/cold-arid urban environments, recent research has increasingly employed scenario-based simulations that test combinations of morphological, material, vegetative, and cultural strategies. These scenarios are typically modeled using ENVI-met, CFD, or hybrid simulation platforms. One scenario class emphasizes urban form optimization, where changes in the height-to-width (H/W) ratio and reductions in the sky view factor (SVF) are applied to generate more shading and reduce solar gain. For example, Teshnehdel et al. (2020) demonstrated in Tabriz that increasing tree density and adjusting building layouts led to PET reductions of up to 5 °C during summer afternoons. Similarly, Ali-Toudert & Mayer (2006) used CFD simulations to show how narrow canyon-like streets with higher H/W ratios reduce daytime thermal load in desert cities.Another frequently simulated scenario includes the application of high-albedo materials on pavements and facades.

Yuan et al. (2023) tested retro-reflective wall coatings in Toyohashi (Japan) and found that higher albedo materials could reduce surface temperatures and improve UTCI scores by 2–3 °C, especially in exposed zones. Vegetation-based cooling strategies—using trees, green walls, or bioswales—are often modeled as a key scenario, especially in urban parks or residential precincts. In a case study from Isfahan, Behzad & Guilandoust (2024) showed that adding vegetative elements around historic plazas could lower PET by approximately 4.2 °C. However, several authors, including Banerjee et al. (2024) and Mahdavi Nejad et al. (2024), caution against over-reliance on vegetation in arid contexts with water scarcity, advocating for adaptive combinations of artificial shading and drought-tolerant planting. In parallel, simulations involving vernacular design scenarios—such as inward-facing courtyards, thick earthen walls, and shaded passages—have proven thermally effective. For instance, Mahdavinejad et al. (2024) compared traditional Iranian courtyards with modern open spaces in Bushehr, concluding that the former offered thermal neutrality even at PET levels exceeding 36 °C, owing to their passive cooling and enclosure. Recent studies also recognize behavioral adaptation as a soft scenario. While not directly simulated, observational research by Zhu et al. (2024) and Bacha et al. (2024) suggests that cultural norms like mid-day activity avoidance or flexible dress codes modulate subjective comfort thresholds, and should be integrated into predictive modeling.

These scenario-based frameworks reveal that no single solution is universally effective. Instead, multilayered strategies, combining physical design with social and environmental considerations, offer the most promising results. Future work should integrate these scenarios into climate projection-based models, particularly for cities in BSk and BWh zones like Tabriz, Isfahan, Cairo, and Biskra.

What is the relationship between the city's physical components, comfort indicators, and microclimatic parameters?

Sky View Factor (SVF)

Sky View Factor (SVF) plays a critical role in regulating microclimatic conditions in urban environments. While high SVF values correspond to greater sky exposure and increased solar radiation—often resulting in elevated daytime temperatures—lower SVF values, typically found in narrow streets or shaded urban canyons, can significantly reduce direct solar gain. This shading effect helps moderate surface and air temperatures, particularly in hot climates, thereby enhancing outdoor thermal comfort. The review indicates that 24% of studies have investigated SVF's impact, with findings suggesting that optimizing SVF—not necessarily minimizing it—through strategic urban design (e.g., vegetation, building orientation, and street geometry) can effectively mitigate thermal extremes. Therefore, moderate SVF values, which balance solar access and shading, are generally most effective for thermal regulation, especially in climates prone to heat stress.(Wang & Akbari, 2014)(Detommaso et al., 2021; Manavvi & Rajasekar, 2021).

Height-to-Width Ratio (H/W Ratio)

The H/W ratio describes the proportion of building heights to the width of the streets or open spaces. A higher H/W ratio can create shaded areas, reduce direct solar exposure and thus lowering temperatures. However, it can also impede airflow, potentially leading to warmer microclimates in poorly ventilated areas. The article indicates that 24% of the studies considered the H/W ratio. Results showed that careful planning of building heights and street widths can significantly influence thermal comfort. (Abd Elraouf et al., 2022; Ben Ratmia et al., 2024).

Albedo

Albedo is the measure of reflectivity of surfaces, with higher values indicating more reflection of solar radiation. Surfaces with high albedo (e.g., light-colored materials) reflect more solar radiation, reducing heat absorption and surface temperatures. This can lower the overall thermal stress in urban areas. About 54% of the studies examined the role of albedo. These studies concluded that using high-albedo materials in urban design can help mitigate urban heat island effects.(Aghamolaei et al., 2021; Teshnehdel et al., 2020).

Vegetation Type and Canopy

Vegetation provides shade, reduces surface temperatures through evapotranspiration, and enhances air quality. Different types of vegetation and canopy densities can significantly affect microclimatic conditions. Studies focusing on vegetation types and canopies accounted for a smaller percentage (4-10%). However, they highlighted the critical role of green infrastructure in improving urban thermal comfort.(Detommaso et al., 2021; Teshnehdel et al., 2020).

Table 5. Overview of studied urban morphology, greenery, and configuration parameters.

STUDIED BUILT ENVIRONMENT	NUMBER OF STUDIES	PERCENT OF THE TOTAL NUMBER OF STUDIES (%)
SVF—SKY VIEW FACTOR	12	24%
H/W—HEIGHT/WIDTH ASPECT RATIO	12	24%
ALB—ALBEDO	27	54%
VT—VEGETATION TYPE	2	4%
VC—VEGETATION CANOPY	2	4%
LAD—LEAF AREA DENSITY	5	10%
COL—COLOR	24	48%

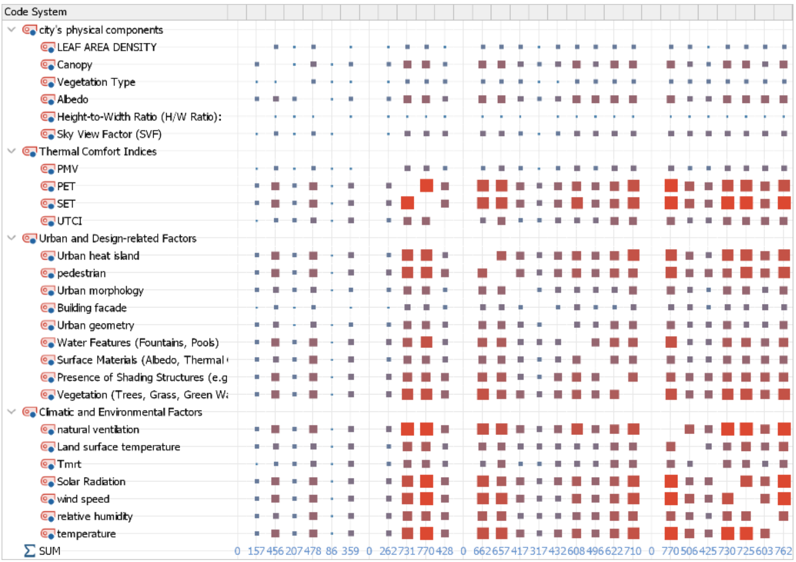


Figure 12. Code Relations Browser tool, illustrates the co-occurrence relationships among three main categories of variables: city's physical components, thermal comfort indices, and climatic and urban design-related factors.

Figure 12., generated by the Code Relations Browser tool, illustrates the co-occurrence relationships among three main categories of variables: city's physical components, thermal comfort indices, and climatic and urban design-related factors. The observed patterns indicate that changes in the city's physical structure directly and indirectly influence the urban microclimate, ultimately affecting citizens' thermal comfort conditions.

First, relatively strong correlations are observed between physical components such as Leaf Area Density, Vegetation Type and Canopy, Albedo, Height-to-Width Ratio (H/W Ratio), and Sky View Factor (SVF) with thermal comfort indices, particularly PET and UTCI. These correlations suggest that the quality and configuration of physical elements can significantly modify comfort indices by altering solar exposure, wind flow, and ambient temperature.

Second, climatic parameters such as air temperature, relative humidity, wind speed, and solar radiation show the strongest connections with thermal comfort indices. In particular, the PET index exhibits high sensitivity to changes in temperature and radiation, underscoring the importance of managing solar exposure and mitigating Urban Heat Island (UHI) effects.

Third, urban design-related factors—including urban geometry, surface materials, and the presence of green cover and shading structures—act as intermediaries between physical components and climatic parameters. By influencing wind flow, reducing or increasing direct solar exposure, and moderating surface temperatures, these factors shape the pathway through which the city's physical form affects thermal comfort.

Software Trends – A Critical Perspective

Although the reviewed studies employed a range of simulation tools—including ENVI-met, CFD, OpenFOAM, and Ansys—critical comparative evaluations of their accuracy, limitations, and contextual suitability are lacking. ENVI-met remains dominant due to its ease of use and built-in vegetation modeling, yet several studies fail to disclose calibration or validation procedures, particularly under dry and hot/cold-arid climate conditions where its default assumptions (e.g., soil moisture, vegetation evapotranspiration) may not hold true. CFD tools offer finer control and higher resolution but are computationally intensive and often applied to idealized geometries detached from real urban complexity.

Strikingly, emerging tools such as Ladybug and Butterfly, which offer integration with Rhino/Grasshopper environments and support parametric design workflows, are underrepresented—despite their potential for iterative urban design feedback. This underutilization may reflect not only technical barriers but also a gap in interdisciplinary collaboration between urban designers and environmental engineers. The fragmented application of software tools reveals a methodological gap in thermal comfort research: simulations are often used as ends in themselves, rather than being embedded within an adaptive, participatory, or design optimization framework.

Future studies should interrogate software choice more critically—not only in terms of simulation capacity, but also regarding transparency, adaptability to arid-specific bioclimatic contexts, and capacity to incorporate behavioral or psychological parameters.

Urban Components and Microclimatic Parameters – Toward Integrative Understanding

The reviewed literature often treats urban form parameters such as SVF, H/W ratio, albedo, and vegetation in isolation. However, a critical shortcoming is the lack of modeling their combined and synergistic effects. For instance, while a high H/W ratio can reduce solar radiation, it may simultaneously reduce wind flow and trap heat if paired with low-albedo materials or insufficient vegetation. Similarly, albedo and SVF interact: high-albedo surfaces are more effective in open spaces (high SVF), while their benefit may be negligible in narrow canyons.

Only a limited number of studies explored these compound relationships through parametric sensitivity analysis or scenario simulations. Even fewer validated such results against empirical or field-based measurements. This undermines the reliability of proposed design guidelines and may lead to overgeneralized conclusions.

Critically, vegetation—while often modeled for its cooling potential—is rarely assessed against its ecological cost in arid zones. Water scarcity, maintenance burden, and long-term viability are frequently ignored in favor of immediate thermal performance metrics. Similarly, behavioral and social adaptation practices (e.g., shade-seeking, seasonal activity shifts) are modeled superficially or entirely excluded from the environmental-physical narrative.

To advance the field, future research should prioritize integrative modeling approaches that:

- Analyze the interactions among SVF, H/W, albedo, and vegetation rather than assessing them in isolation;
- Couple physical simulation with empirical calibration and on-site microclimatic measurements;

- Incorporate human-environment feedback loops involving psychological adaptation, socio-cultural practices, and behavioral thermoregulation;
- Acknowledge urban typology-specific dynamics, such as traditional courtyard houses vs. contemporary high-rise blocks, rather than applying generalized urban form prescriptions.

By moving beyond a reductionist approach and embracing contextual complexity, thermal comfort research can better inform policies and design practices suited to hot/cold-arid urban realities.

Discussion

This systematic review critically analyzed 50 peer-reviewed studies to map the landscape of simulation-based outdoor thermal comfort (OTC) research in hot and cold-arid urban environments. The findings reveal several prominent, and often interdependent, trends, gaps, and methodological challenges that warrant detailed discussion in the context of the broader literature.

Geographical Imbalances and the Imperative for Index Calibration

Our analysis confirms a significant geographical concentration of research in mid-latitude countries like China, India, and Iran (Figure 3). This focus, while yielding valuable insights for temperate and semi-arid zones, has inadvertently marginalised extensive arid and hyper-arid regions, particularly in North Africa and the Arabian Peninsula. This geographical bias echoes concerns raised by earlier reviews (e.g., Lai et al., 2020; Kumar & Sharma, 2020), which highlighted that OTC research is often clustered in economically developing yet rapidly urbanizing nations, leaving critical climate zones understudied.

More critically, the pervasive use of standard thermal indices like PET, UTCI, and PMV without region-specific calibration is a fundamental limitation. Our synthesis corroborates the findings of Elraouf et al. (2022) and Gomaa et al. (2024), who argued that indices developed for temperate climates fail to capture the adaptive behaviors and physiological acclimatization of populations in arid regions. For instance, the finding that thermal neutrality in shaded conditions in cities like Tehran occurs at PET values exceeding 34°C—significantly higher than established thresholds—is not an anomaly. Instead, it aligns with a growing body of evidence from hot-dry climates (e.g., Galal et al., 2020 in Aswan; Beckett et al., 2017 in rammed earth structures) that underscores the plasticity of human thermal perception. This consistent discrepancy strongly suggests that the unqualified application of these indices can lead to erroneous conclusions and ineffective design guidelines, potentially promoting energy-intensive cooling solutions where passive, adaptive strategies would suffice.

The Dominance and Pitfalls of Simulation Tools

The trend analysis clearly establishes CFD as the dominant simulation tool in recent years (Figure 10), followed by ENVI-met. The ascendancy of CFD is understandable, given its ability to model complex airflow and pollutant dispersion with high resolution, as demonstrated in studies like Ioannidis et al. (2024) and Chockalingam et al. (2023). However, our review identifies a critical shortcoming: a widespread lack of robust model validation against empirical field data. This issue is particularly acute in arid environments, where default parameters in tools like ENVI-met for soil moisture and plant physiology are often misaligned with local conditions. Johannes Brozovsky et al. (2021) emphatically demonstrated the necessity of validation for reliable microclimate assessment, a step that is regrettably omitted in many of the reviewed studies.

Furthermore, the underutilization of emerging, design-integrated tools like Ladybug and Butterfly represents a missed opportunity for interdisciplinary collaboration. While CFD provides deep analytical insight, tools like Ladybug, operating within parametric design environments, can facilitate iterative, performance-driven urban design from the earliest stages, a capability less emphasized in the current corpus of arid climate research. This finding suggests a lingering gap between environmental simulation and practical urban design workflows, a challenge that future research must bridge.

Re-evaluating Mitigation Strategies: Beyond Universal Greening

The review of mitigation strategies (Table 4) reveals a strong, and sometimes uncritical, promotion of vegetation as a primary cooling mechanism. While the efficacy of greenery in reducing PET is undeniable, as shown by Teshnehdel et al. (2020) and Behzad & Guilandoust (2024), its feasibility in water-scarce environments is a paramount concern that is frequently sidelined. This aligns with critiques by Xu et al. (2019), who warned against the ecological costs of "imported" green solutions in arid landscapes.

In contrast, our review highlights the undervalued potential of vernacular urban design strategies. The superior thermal performance of traditional elements like courtyards (Mahdavinejad et al., 2024), narrow alleys (sabats), and high thermal mass materials offers a blueprint for context-sensitive, low-energy comfort. These strategies, refined over centuries of climatic adaptation, provide shading, promote nocturnal cooling, and leverage evaporative effects without imposing unsustainable water demands. The comparative absence of these vernacular strategies from mainstream simulation research points to a significant cultural and contextual blind spot. A more balanced approach, integrating drought-tolerant native vegetation with passive architectural cooling—such as the use of high-albedo materials and optimized urban geometry (Yuan et al., 2023; Ali-Toudert & Mayer, 2006)—is urgently needed.

The Neglected Human Dimension: Behavioral and Cultural Adaptation

Perhaps the most consistent gap across the reviewed literature is the inadequate integration of behavioral and socio-cultural factors into simulation frameworks. While studies like Zhu et al. (2024) and Bacha et al. (2024) empirically observe adaptive behaviors such as activity scheduling, shade-seeking, and clothing adjustment, these dynamic human responses are rarely formalized in predictive models. This omission creates a disconnect between physically modeled comfort conditions and actual human experience. The work of Aljawabra & Nikolopoulou (2018) has long argued that thermal comfort is not merely a physiological state but a psychological adaptation influenced by cultural norms and expectations. The failure to incorporate these "soft" adaptive factors risks producing technically accurate but humanly irrelevant comfort assessments, ultimately limiting the real-world impact of OTC research.

Synthesis and Forward Look

In synthesis, the current state of OTC research for arid environments, while methodologically sophisticated in its use of simulation tools, is characterized by three critical imbalances: a geographical imbalance in study sites, a methodological imbalance in the calibration and choice of tools and indices, and a contextual imbalance in the consideration of ecological and cultural constraints. Moving forward, the field must pivot towards a more integrative and localized paradigm. This includes:

Prioritizing the recalibration of thermal indices for arid zones through extensive field surveys.

Mandating empirical validation for all simulation studies to enhance reliability.

Formally incorporating behavioral adaptation and cultural practices into modeling frameworks.

Championing a hybrid design approach that synergizes the best of vernacular wisdom with technological innovation, always mindful of ecological constraints like water scarcity.

By addressing these priorities, OTC research can evolve from merely diagnosing thermal problems to providing culturally attuned, ecologically sustainable, and socially resilient design solutions for the world's rapidly growing arid cities.

Conclusion

This critical systematic review has synthesized the past four years of simulation-based research on outdoor thermal comfort (OTC) in hot and cold-arid urban environments. By analyzing 50 peer-reviewed studies, we have moved beyond a mere summary of findings to identify fundamental tensions and imbalances that currently constrain the field. Our analysis leads to three overarching conclusions that demand a paradigm shift in how OTC is studied and applied in arid contexts.

First, the field is currently hampered by a **triple imbalance**. The *geographical imbalance*—with research concentrated in a few mid-latitude countries—leaves vast arid regions like North Africa and the Arabian Peninsula critically understudied. The *methodological imbalance* is evident in the pervasive, yet uncalibrated, use of thermal indices like PET and UTCI, whose thresholds, derived from temperate climates, consistently fail to capture the adapted thermal perception of arid zone populations. Furthermore, an over-reliance on advanced simulation tools like CFD and ENVI-met, often without rigorous empirical validation, questions the real-world accuracy of many findings. Finally, a *contextual imbalance* persists, where universalist solutions like intensive urban greening are promoted without due consideration for local ecological constraints, particularly water scarcity, while proven vernacular cooling strategies remain on the margins of academic discourse.

Second, this review unequivocally demonstrates that achieving thermal comfort in arid cities is not merely a biophysical challenge but a **socio-ecological one**. The most significant gap identified is the near-complete omission of behavioral and cultural adaptation from simulation frameworks. Practices such as activity scheduling, clothing choices, and shade-seeking are key determinants of outdoor comfort, yet they are rarely formalized in predictive models. Ignoring this human dimension produces a disconnect between simulated comfort and lived experience, limiting the practical relevance of research outcomes for urban planners and designers.

Therefore, third, we propose a decisive shift towards **context-sensitive and integrative modeling**. The framework presented in Figure 13 offers a pathway for this shift. Future research must:

1. **Prioritize the recalibration of thermal indices** for arid zones through extensive longitudinal field studies that couple physical measurements with subjective comfort surveys.
2. **Embrace hybrid methodologies** that couple high-resolution simulation with mandatory field validation and the integration of remote sensing data (e.g., LST, NDVI) to bridge the scale between microclimate and urban form.
3. **Formally incorporate socio-behavioral factors** into comfort models, transforming OTC assessment from a purely physical exercise into a holistic human-environment evaluation.
4. **Champion vernacular and passive design strategies**—such as optimized urban geometry, high-albedo materials, and water-efficient landscaping—as ecologically intelligent and culturally resonant alternatives to imported, resource-intensive solutions.

In conclusion, the pursuit of outdoor thermal comfort in the world's arid cities stands at a crossroads. The prevailing approach of applying standardized tools and solutions is proving inadequate. By embracing a new paradigm that is geographically inclusive, methodologically rigorous, ecologically mindful, and culturally attuned, researchers and practitioners can collaboratively design urban spaces that are not only thermally comfortable but also sustainable, resilient, and truly responsive to the unique challenges of arid landscapes.

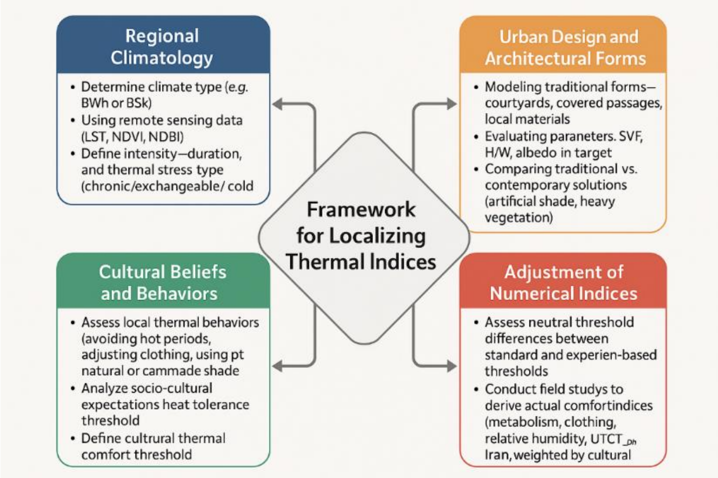


Figure 13. Framework for Localization of Outdoor Thermal Comfort Indices in Arid Urban Climates

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