

# Optimizing Microclimatic Design in Urban Environments: Study of Methods and Strategies for Residential Clusters

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**Abstract** Urban residential areas are confronted with substantial challenges in maintaining outdoor thermal comfort due to the urban heat island effect. As the ramifications of climate change continue to escalate, it becomes increasingly vital for the well-being of inhabitants to improve the outdoor comfort of urban dwellings. The purpose of this study is to conduct an exhaustive review of microclimate design optimization to discern and assess a range of methodologies, tools, and design elements that contribute to the efficient creation of microclimatic-sensitive designs. The study adopts a systematic literature review method to investigate seminal publications, studies, and models pertaining to the optimization of microclimatic design. The study focuses on the different computational models, including RayMan and ENVI-met, and analyzes various context-specific design factors that impact microclimatic conditions in-depth. The review delves into context-specific design factors such as vegetation, building orientation, and urban morphology, emphasizing the importance of scale sensitivity, local adaptation, and zoning flexibility in optimizing microclimatic conditions. The analysis highlights a notable lacuna in the existing body of research regarding the optimization of microclimatic design for low-height residential units within urban clusters. The prevailing body of research mostly focuses on expansive group housings and institutional structures, neglecting the distinct issues and prospects associated with smaller-scale residential

clusters. This gap highlights the need for more targeted research on smaller-scale residential clusters to develop tailored microclimatic solutions. The study can help address these overlooked areas, and further studies can provide a more holistic understanding of sustainable urban living, ensuring that microclimatic design benefits are equitably distributed across diverse urban environments.

**Keywords** Urban Environment, Urban Microclimate Design, Thermal Comfort, Low-Height Residential Unit, Mitigation Strategies

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## 1. Introduction

Rapid urbanization and human-induced heat have resulted in the Urban Heat Island (UHI) phenomenon, which has a substantial impact on temperatures in metropolitan areas. The combination of urban climate change and rapid urbanization presents significant issues to human health, thermal comfort, energy consumption, and emissions [1]. The severity of the UHI phenomenon on buildings and their occupants necessitates ongoing research into creative ways to alleviate its negative impacts. A comprehensive understanding of microclimatic conditions, which are influenced by elements such as geographical location, climate patterns, and human activity,

is required to unravel the complex relationship between the natural environment and human comfort [2]. The UHI phenomenon exacerbates the effects of urban climate change, necessitating novel ways to mitigate its negative effects on buildings and human health. The planned implementation of green and blue infrastructure, which includes elements such as parks, vegetation, water bodies, and other natural features in urban settings, is an important strategy for tackling this dilemma. These attributes not only serve to reduce local temperatures, but they also contribute to urban sustainability, resilience, and competitiveness [3]. By combining green and blue areas, urban designers can create cooler surroundings that improve thermal comfort and general well-being.

Understanding and treating urban microclimates is critical, as they are influenced by geographical location, built environment characteristics, and human activity. Microclimates significantly affect local temperature changes, humidity levels, and wind patterns, all of which have a direct impact on urban populations' health, comfort, and energy usage. As a result, developing urban places with a microclimate-sensitive strategy, including strategic material usage, building orientation, and natural buffers, can significantly improve city people's quality of life while reducing the city's environmental imprint. Thus, we may infer that urbanization has profoundly transformed the interaction between built and natural environments, intensifying the Urban Heat Island (UHI) effect and thermal discomfort, particularly in densely populated cities. While substantial research has focused on central business districts and high-rise developments, low-height residential clusters, which are critical for accommodating diverse socio-economic groups, remain understudied [4]. These areas often face unique microclimatic challenges, including limited access to cooling infrastructure, suboptimal spatial configurations, and constrained financial resources for mitigation strategies.

This paper addresses these gaps by exploring tailored microclimatic strategies for low-height residential clusters, considering their specific spatial and socio-economic contexts. Unlike previous studies that generalize UHI mitigation strategies, this research emphasizes innovative frameworks and case-specific applications. By integrating computational modelling, hybrid solutions combining green and blue infrastructure, and socio-economic analysis, the study contributes to both academic discourse and practical urban planning efforts.

### 1.1. Microclimatic Design

Numerous studies in the literature database have investigated the effects of urban design elements on open-space microclimates in a variety of urban environments and climates. However, these studies frequently lack a comparison basis for determining the relative importance of factors in each urban setting [5].

Street and courtyard geometric characteristics such as aspect ratios, orientation, openings, and canopies have been studied to see how they affect comfort, energy fluxes, and wind patterns [6]. Microclimates in open spaces in cities vary depending on factors such as urban layout, vegetation, water levels, and surface features. Inappropriate manipulation of these parameters contributes to environmental harshness, resulting in greater temperatures in urban areas than in suburbs—the well-known urban heat island (UHI) phenomenon [7]. Heat-trapping by urban geometry, urban surface features, changes in vegetation cover, and anthropogenic heat input are all major contributors to UHI. Microclimatic design is the intentional planning and manipulation of environmental variables inside specific localized spaces, usually on a smaller scale than the overall climate [8]. The technique involves intentional interventions in the built environment, landscape, and architectural features to produce optimal microclimates that improve occupant comfort, energy efficiency, and general well-being [9], [10].

### 1.2. Importance of Thermal Comfort in Design

Understanding thermal comfort is pivotal to architectural concerns and sustainable design, particularly in microclimatic design optimization. Modern thermal comfort models recommend a narrow temperature range for all buildings, climates, and populations, treating occupants as passive thermal recipients [11]. However, this approach may lead to energy-intensive environmental control regulations, prompting a shift towards microclimatic design emphasizing thermal comfort control [12]. This trend has resulted in the broader use of psychometrics in HVAC design, challenging comfort standards by introducing fluctuating interior temperatures.

Thermal comfort, influenced by the body's heat balance, is subjective in microclimatic design optimization and depends on ambient temperature, radiant temperature, relative humidity, air velocity, metabolic rate, and clothing insulation [12]–[14]. Understanding these variables is crucial for planning and developing building air conditioning systems in microclimatic conditions, considering the significant energy consumption in the construction industry [7], [15]. Microclimatic design optimization extends to outdoor urban settings, revealing the complexity of thermal comfort issues in these areas. Balancing thermal conditions is essential for microclimatic design energy efficiency and sustainability, with a focus on comfort and its positive effects on the microclimate and human well-being in designed spaces.

This introduction offers the framework for a thorough discussion of Microclimatic Design Optimization and its critical role in mitigating thermal comfort issues. The following sections will describe microclimatic design, examine the role of thermal comfort in design

considerations, and explain the complex relationship between building design, energy efficiency, and occupant well-being. The ultimate purpose of this research is to add to the discussion about sustainable and comfortable urban living by undertaking a thorough assessment of critical issues of thermal comfort vis-a-vis microclimatic design by addressing the following research questions:

- I. What are the different methods adopted to study microclimatic design optimization?
- II. What processes have been adopted to use these different methods in literature?

## 2. Literature Review

The Urban Heat Island (UHI) effect is a well-documented phenomenon exacerbated by urbanization. Mitigation strategies, including urban heat mitigation techniques, thermal adaptation, and computational modelling, have demonstrated efficacy in improving thermal comfort. However, their applicability to low-height residential clusters remains inadequately explored. Existing literature highlights the effectiveness of computational tools, such as ENVI-met and RayMan, in simulating microclimatic scenarios [2], [16]. However, these tools are often applied at larger urban scales, with limited consideration of the spatial and financial constraints inherent in smaller residential areas. Similarly, studies on zoning and building codes [5] emphasize their impact on energy efficiency but fail to address their scalability in low-income neighbourhoods. Socio-economic constraints further complicate UHI mitigation in low-height residential clusters. Research indicates that initial costs and maintenance requirements limit the adoption of green infrastructure in resource-constrained communities [17]. Yet, few studies provide actionable policy recommendations to address these barriers.

This review identifies a significant gap in adapting existing methodologies to the unique spatial, financial, and socio-cultural characteristics of low-height residential clusters. This paper seeks to fill this gap by proposing novel, context-specific solutions and highlighting the importance of stakeholder engagement in strategy design. The following section elaborates on the key aspects in the literature on Microclimate design optimization and thermal comfort. The deliberations provide a basis for the analysis of different methods and are processed for further evaluation:

### 2.1. Importance of Microclimatic Design

Microclimatic design emerges as a critical technique for creating sustainable and comfortable urban environments, particularly when tackling issues such as the urban heat island effect. As cities grow, the concentration of

heat-absorbing surfaces like concrete and asphalt raises temperatures, aggravating thermal discomfort and increasing energy usage. These elevated temperatures, which are characteristic of the UHI phenomena, not only harm urban liveability but also contribute to local climate change impacts. Effective microclimatic design is thus critical in mitigating UHI by examining how urban landscapes might better manage heat and provide cooling.

One of the most effective tactics in this design approach is the incorporation of natural features like trees and vegetation. Green spaces contribute significantly to urban cooling via mechanisms such as shade and evapotranspiration. However, the cooling effects of green infrastructure are determined by the vegetation's unique properties, such as species selection, covering, and placement [18]. These elements must be carefully evaluated in order to maximise the benefits of green spaces in terms of UHI mitigation and thermal comfort [19], [20]. Thus, intelligent landscape design is critical to realising the full potential of urban green spaces in lowering the urban heat island effect.

Building heights, orientations, and the balance of ventilation and shade are all important factors when implementing microclimatic design in urban planning. The complexity of the built environment necessitates careful consideration, particularly in warm-humid climates where striking this balance is important [4]. Site-specific characteristics add another layer of complexity, as evidenced by studies such as the one done [4], emphasizing the continual challenge of striking a balance and the necessity for a sophisticated understanding of the local context.

The interaction of microclimatic design, outdoor thermal comfort, and sustainable urban development needs integrated and context-specific techniques [21], [22]. The techniques give insights from such considerations to aid the well-being of urban residents and the overall livability and vitality. Therefore, to navigate the contemporary urban challenges, a holistic awareness of these aspects is essential for effectively designing microclimate-sensitive buildings.

#### 2.1.1. Microclimatic Zoning

Rapid urban population development and increased building density have had a substantial impact on microclimates, resulting in the Urban Heat Island (UHI) effect. Urbanization leads to increased urban temperature and understanding the intricate interplay of physical phenomena in urban microclimates is critical. This leads to microclimatic zoning tools, which are essential to urban environmental management. It divides zones depending on temperature, humidity, wind patterns, and solar radiation exposure. Microclimatic zoning goes beyond conventional categories like Köppen and captures local climatic nuances that are typically missed [23], [24]. This method is critical for understanding intra-urban heat disparities, as it provides precise maps of changes that influence urban

heat-reduction initiatives [25]. Numerous factors have been investigated in the studies, such as the fact that tree canopy cover reduces air temperature through evapotranspiration and shade. Similarly, urban form, impacted by structures and density, has an impact on local climatic dynamics, highlighting the need for additional study to bridge the gap between urban climate understanding and zoning rules [26], [27]. The researchers have established that climate zoning helps urban planners understand local climate dynamics, resulting in insights for sustainable and climate-resilient city planning in the face of continuous urbanization, climate change, and expansion [28]. Reflective materials on surfaces can have an impact on comfort and energy balance, emphasizing the importance of addressing microclimatic problems for long-term urban development [29].

### 2.1.2. Green Spaces and Thermal Comfort

Urban heat island (UHI) concerns, exacerbated by increased urbanization, have driven an increase in studies into mitigation techniques, with a focus on the cooling potential of urban green spaces [30]. The notion started with Chandler's 1962 introduction of the 'park cool island' (PCI) effect emphasizes the temperature-lowering effects of green spaces, revealing decreases ranging from 2 to 8 K [19]. Studies emphasize the importance of understanding the shape, organization, and layout of green patches, using measures such as the Land Shape Index (LSI), Patch Density (PD), and Edge Density (ED) [5], [13], [31]. However, the research finds inconsistencies in the relationship between Land Surface Temperature and ED and PD, leading to calls for numerical modelling tools such as the ENVI-met® model to understand plant-air interactions fully [32].

Similarly, Physiologically Equivalent Temperature (PET) as a thermal index demonstrates the importance of spatial design on thermal comfort [18]. There are also studies which emphasize the importance of green spaces with trees, canopies, and unique designs in increasing thermal comfort [2]. Additionally, PD and ED research provide vegetation-dependent results, further highlighting the complex dynamics of spatial layout on thermal comfort [19]. Later, in studies it was also observed that cooling efficacy of distributed green patches is governed by characteristics such as size, shade, and the precise spatial arrangement of individual patches, providing vital information about their potential to reduce urban heat and increase human comfort [33].

## 2.2. Need for Microclimatic Design Optimization

With the escalating population, the urban environment becomes a furnace that puts people through different kinds of stress, especially the meso and microclimates that are changed by alterations in surface structures [16], [27]. Because cities are growing, these changes affect Urban

Heat Islands (UHI) and change radiation flows, which are harmful to people's health [6]. Hence implying, it is necessary to combine meteorological and thermo-physiological factors to get a full picture of the climate in cities and neighbourhoods [34].

Although there have been investigations to figure out the different temperature aspects of city life, which is necessary for making comfortable microclimates, the need to understand human temperature comfort, especially in the summer when the UHI stays in place all night, is still a pertinent issue [18]. As cities change their climate, it has many effects; for people's health and for correct estimates of building energy needs, it is imperative to understand wholesomely the different microclimates that exist within cities [35]. Furthermore, the anticipated changes in urban microclimates are caused by human activities, which affect not only temperatures but also patterns of precipitation, extreme weather, and the spread of pollutants. In turn, these changes impact how much energy buildings use and the quality of life for people living in cities [34], [36]. As climate change continues, it is evident that studies have attempted to understand how to reduce the phenomenon, such as the UHI effect, by altering cool surfaces and urban greenery to water bodies on different scales [30], [37].

There also have been attempts to understand microclimatic optimization in the context of human well-being. However, the link between changes in people's health and changes in the surroundings still leads to serious repercussions, which makes it even more important to look at urban well-being as a whole [13]. Globalization, changes in population, climate change, and new social systems all affect each other in complex ways that put people's well-being at risk, requiring a complex understanding of how cities affect health [31], [32]. This is why criteria for reviewing public health policies in cities had to be created. Uncontrolled urban growth without careful planning makes problems like environmental stressors, transport problems, and social and economic divisions worse. Promoting physical, social, and neighbourhood resources is still an important idea for the health of cities [23], [30]. All the physiographic and other elements, such as water, heat, radiation, wind, and air, shape an urban environment with man-made surfaces, tall buildings, and pollution [38]. However, an extensive study that analyses their impact on the layout of the residences and neighbourhoods of rise still remains to be explored as standardized key guidelines for different context-based studies [7].

## 2.3. Energy Efficiency Considerations

Local microclimate phenomena, influenced by street geometry, vegetation, and building materials, have a significant impact on air temperature, humidity, ventilation, and overall environmental quality [11], [21], [26]. Addressing these issues is critical for improving inter-building thermal comfort and creating

energy-efficient urban environments. Numerical simulations and experimental monitoring programs are critical for understanding the effects of street layout, vegetation, and building materials on local microclimates. These parameters affect not only air temperature, humidity, and ventilation but also the performance of renewable energy source [38], [39]. Mitigating the urban heat island effect and improving microclimates have been extensively researched, with a focus on mapping microclimates and implementing effective mitigation strategies to reduce peak and ambient temperatures [29].

There have been measures such as green infrastructure, particularly urban vegetation, for lowering urban overheating and minimizing the urban heat island effect [23]. Water-based solutions, such as pools, ponds, fountains, and sprinklers, can reduce temperatures by 6-7 degrees Celsius [39]. Furthermore, albedo-increasing solutions such as cool roofs and reflective pavements minimize building cooling energy demand while also improving urban microclimate [30], [40].

To optimize energy efficiency in building design, a comprehensive strategy is required, taking into account the complex interactions between architecture, construction, and building service engineering [41]. The building envelope is critical, with insulation, airtightness, and glazing all necessary components. Climate-specific design concepts, such as compact design and well-insulated components in cold regions, energy-efficient fenestration in mild temperatures, and reflective surfaces in hot, dry climates, guide maximum building efficiency [41].

Whole-building simulation tools, such as Energy Plus and WUFI-Plus, make it easier to evaluate construction components and HVAC equipment for compliance with climate-specific design criteria. It is critical to incorporate local climates and cultures in holistic building climate design to provide sustainable energy control that prioritizes user, climate, and cost-effectiveness [16]. Combining comfort and energy demand monitoring provides a thorough understanding of building responses to climate and user behaviour, paving the path for more effective cooling and air-conditioning system optimization [20]. Therefore, in the context of energy efficiency too, urban microclimate optimization is of the essence and requires complete attention of the professionals to cater to the multifaceted impact microclimate sensitive designs.

### 3. Methodology

This literature review adopts a structured approach to exploring microclimatic design optimization in urban residences comprehensively. The systematic search strategy involves querying electronic databases with keywords such as "microclimate design," AND "thermal comfort", AND "Optimization" AND, "mitigation" OR "mitigating strategies". The search was conducted on 14th

May 2024. The search resulted into 1276 papers. The objective is to analyze existing research from 2010 to 2024. Therefore, only 631 papers were shortlisted. Another inclusion criteria were focused on primary articles, reviews, and conference papers that left out pre-prints, reports and book chapters, resulting in 487 papers. To maintain rigour, exclusion criteria eliminate non-peer-reviewed articles, studies not in English, outdated information, irrelevant topics, and narrowly focused research, resulting in 379 papers. In addition, the inclusion of relevant articles is determined by examining the abstract and title of the articles that demonstrate the use of mitigation or optimization strategies in urban climatic design without any inconsistencies. In the end, this produced 51 articles that underwent a thorough examination in the study. Extraction of data emphasizes critical components such as study design, methodologies, discussed tools and strategies, significant findings, and limitations. The methodology section is founded upon the systematic literature review, which provides a methodical and rigorous framework for comprehending the articles and helps in their deliberations [42].

## 4. Microclimatic Design Optimization

Multiple approaches have been used for optimising microclimatic design, each of which plays a vital role in improving the sustainability, comfort, and functioning of urban environments. Climate analysis technologies, such as sophisticated models and software, such as Computational models like ENVI-met and RayMan, offer valuable insights into addressing difficulties like the urban heat island effect. Furthermore, the examination of urban atmospheric microclimates contributes to the formulation of efficient approaches to decrease air temperatures and enhance overall thermal comfort [18]. Assessing the impact of variables such as the positioning of buildings [8], choice of materials [32], and incorporation of green spaces [22] enables the development of designs that are responsive to climate conditions, thereby improving energy efficiency and promoting sustainable development. This knowledge enables professionals to make well-informed choices, leading to the development of urban areas that are both visually appealing and capable of withstanding climate change. In the following sub-sections, the methodologies used in the studies of microclimatic design are discussed:

### 4.1. Climate Analysis Tools

Urban atmospheric microclimate modelling employs sophisticated techniques to understand and tackle the challenges posed by global climate change and the urban heat island effect [43]. Policymakers and researchers use many models to study mitigation measures that could

effectively lower urban air temperatures. ENVI-met and RayMan are commonly cited in the literature as leading choices, each offering distinct features and advantages.

ENVI-met is a Computational Fluid Dynamics (CFD) model that specializes in tackling atmospheric flow and heat transfer issues by applying the Reynolds-Averaged Navier-Stokes (RANS) equations. The latest iteration (v.4) of this model, created by Bruse and released in 2016, is well-known for its intuitive interface and its precise depiction of complex metropolitan geometries, vegetation, and other energy sources like waste heat and water elements [8], [25]. Researchers use ENVI-met due to its optimal balance of complexity, user-friendliness, and cheaper computational costs. Concerns exist about the inadequate testing performed to evaluate all aspects of its capabilities and limits, especially its autonomy from the grid [8]. Rayman, a tool used for atmospheric modelling, is well-known for its widespread application in studying atmospheric microclimates. While it may not have the same dynamic process linkage as ENVI-met, it provides valuable insights into urban microclimates and is used to identify different climatic conditions.

ENVI-met and similar computational models are valuable tools that allow researchers to replicate the urban built environment and atmosphere. The models can be adjusted in size to include entire metropolitan areas or smaller, specific portions, providing flexibility and cost efficiency for urban planners. Modelling urban atmospheric microclimates requires a careful selection of techniques to address the complexities of climate change and urbanization. ENVI-met and RayMan, together with other models, significantly contribute to understanding and assessing mitigation measures [19]. Despite their advantages, both instruments face hurdles and limitations. The cost of deploying measures citywide and the scarcity of quantitative observational data hinder the widespread adoption of mitigation strategies [19]. It is important to recognize the limitations of each instrument and do thorough validation to ensure accurate and reliable results in urban microclimate research. Moreover, for the effective utilization of the tools, One of the primary problems that must be addressed to enable urban planning processes connected to climate change adaptation is the uncertainty associated with climate projections for the future that are integrated with the tool, as well as the methodology required to downscale the data for each scale [44]. Moreover, using the tools to analyse the microclimate at buildings and neighbourhoods and its impact on the city scale is often not accomplished due to the unavailable localized data.

While computational tools like ENVI-met and RayMan provide powerful means of simulating urban microclimate, the practical challenges of implementing these tools in diverse real-world contexts are often underestimated. For instance, although the tools offer a user-friendly interface,

their outputs are highly sensitive to the quality and resolution of the input data [45]. Inadequate data can lead to significant calculation errors, reducing the reliability of the model's projections. For example, in studies conducted on UHI in cities like New Delhi, where detailed vegetation and surface data are lacking, ENVI-met has produced results with substantial deviations from observed conditions [17]. Moreover, the computational demands of these tools, which often require advanced hardware for simulations, present a barrier for municipalities or smaller planning firms that may lack the necessary technical infrastructure [46]. As a result, there is a risk that these models may only be accessible to well-resourced regions, further widening the gap between technologically advanced and undeveloped urban areas in microclimatic planning.

#### 4.2. Comparison of Different Microclimatic Studies

The Table 1 provides an exhaustive examination of diverse methodologies employed to enhance thermal comfort in urban environments and improve the quality of outdoor environments. This compilation examines various facets, including incorporating green spaces into roadways, individual and urban block neighbourhoods, and public spaces, as well as the effects of street orientation, solar access, building orientation, and thermal comfort on diverse residential layouts. Furthermore, the table assesses the impact of renovation strategies, afforestation, and water features on pre-existing residential areas in Shanghai while examining the influence of green roofs and urban vegetation in inner-city residential neighbourhoods [47]. The comparison encompasses urban planning and layout design, providing insights into landscape planning and the influence of green cover on climate resilience while analyzing thermal comfort in densely populated urban areas. As a final point, the table examines instances, including central open spaces amidst urban residential clusters and ancient residential areas confronted with climate resilience challenges [48]. The objective of this comparative analysis is to elucidate the intricacies of each microclimatic study, thereby furnishing a comprehensive comprehension of the varied approaches utilized to improve outdoor environments in distinct urban settings.

The reviewed research highlights considerable difficulties in the implementation and reliability of microclimate optimisation strategies, mostly due to context-dependent variables that restrict the generalisability of findings across various urban settings. A primary concern pertains to the climatic specificity of the results. Replacing asphalt with reflecting materials such as cool concrete has demonstrated significant decreases in surface temperatures in hot metropolitan regions; however, this strategy may be inappropriate for cooler climates where heat retention is beneficial.

**Table 1.** Microclimatic Studies and Themes

Sl no.	Context of the paper	Author	Methods/ Tools	Variables	Relevant Findings	Challenges
1	<b>Improving Outdoor Environment</b> Green Spaces in public areas, Individual, Urban block neighbourhoods, Roadways	[7], [9], [22]	1. ENVI-met and PMV index were used for simulations.	1. Cool concrete instead of asphalt. 2. Surface reflectivity. 3. Cool materials. 4. Permeable surfaces. 6. Vegetation such as trees. 7. Green roofs Include living walls.	1. Combined strategies effectively reduced temperatures. 2. Reflective materials for roads and replacing asphalt with concrete led to significant temperature decreases. 3. Resulted in lowered surface and air temperatures	1. Reflective materials may not perform the same in colder climates, where heat retention is necessary. 2. High cost of replacing road materials with concrete in existing infrastructure 3. Long-term performance of reflective materials may degrade, affecting replicability over time.
2	<b>Building Orientation and Thermal Comfort.</b> Street orientation, Building shape, solar access, urban canopy, Six different residential building layouts	[49], [50]	1. ENVI met software ranging from 0.5 to 10 meters. 2. Physiological Equivalent Temperature (PET). 3. Simulation and Evaluation.	1. Optimized building layout and height. 2. Strategic integration of vegetation.	1. Insights on optimizing canopy extension for pedestrian comfort, emphasizing layout impacts: 2. Parallel layout: Faster temperature changes, distinct patterns. Focus on maximizing thermal comfort in pedestrian spaces.	1. Differences in urban layouts, building heights, and vegetation types across cities make the direct application of results difficult. 2. Local wind patterns and solar exposure greatly influence effectiveness, making it hard to generalize findings across different cities.
3	<b>Green Roofs and Urban Vegetation Impact</b> Cool roofs and green roofs, inner-city residential neighbourhoods, Various vegetation types affect the thermal environment	[19], [51], [52]	1. WRF 3.8 with UCM for UHI effect. 2. PET calculation with RayMan Pro. Employed 3. ENVI-met for material simulation.	1. Wind speed. 2. Mean radiant temperature. 3. Rooftop 4. Vertical cooling effects of vegetation.	1. Cool roofs outperform green roofs. 2. Green roofs have minimal street-level cooling under certain conditions. 3. Different vegetation types offer varying degrees of cooling efficacy.	1. Green roof effectiveness is limited in cold or highly humid environments where the vegetation may not thrive. 2. Green roofs require regular upkeep and irrigation, which may not be feasible in regions with limited water resources or maintenance budgets. 3. Structural limitations of buildings may prevent the installation of green roofs in older or high-rise structures.
4	<b>Microclimate and Renovation Strategies</b> Afforestation and water features, Renovation on existing residential areas in Shanghai.	[53], [54]	1. The KECHEN turbulence model, with a roughness value of 0.03 m. 2. ENVI-met 3. EnergyPlus.	1. Building density 2. Materials 3. Vegetation 4. Green space (G) 5. Enhancing pavement reflectivity (P) 6. wall material reflectivity (W) 7. Reflective or green roof materials (R)	1. Impact on summer microclimate: Climbing plants > grassland > shrub > tree > water. 2. Impact of landscape elements on microclimate: 3. G and R decrease the annual air conditioning load, while P and W increase it. 4. G affects Ta and RH. 5. P reduces Ta in winter and summer. 6. W reduces Ta and sun radiation. 7. Increasing roof reflectivity (R2, R3) acts similarly to W for R.	1. Reflective or permeable materials used in the study may not be readily available in other regions, affecting replicability 2. Different regions may prefer particular landscaping elements (trees vs. shrubs) based on aesthetic or cultural preferences. 3. Budget limitations may affect the feasibility of large-scale retrofitting projects involving reflective materials or extensive afforestation.

Table 1 continued

<p>5</p>	<p><b>Urban Planning and Layout Design</b> Comparing between three courtyards, Thermal comfort in residential areas, Densely populated urban areas</p>	<p>[55]–[57]</p>	<p>1. ENVI-met and BioMET. Validation of the model. 2. Creation of 3D models for scenarios with varying floor space index (FSI) using ENVI-met software.</p>	<p>1. Air temperatures within courtyards. 2. Outdoor thermal comfort assessment. 3. Townhouse layout 4. Building design 5. Tree planting. 6. Consideration of floor space index (FSI).</p>	<p>1. Courtyard performance and urban design impact microclimates.  Factors such as shading, vegetation, and surface albedo.outdoor-indoor temperature and urban planning elements like the Floor Space Index (FSI).</p>	<p>1. High-density areas may not have sufficient space for courtyards or vegetation, limiting the replicability. 2. Different species of trees may have varying growth rates, and maintenance may impact the cooling effect in regions with different climates. 3. Different cities have different levels of heat islands, affecting the efficacy of courtyard designs in providing cooling.</p>
<p>6</p>	<p><b>Landscape Planning and Green Cover Impact</b> The old residential area faces climate resilience challenges. Central open space within a residential project, Urban Residential Clusters</p>	<p>[47], [58]</p>	<p>1. Questionnaire surveys 2. Field measurements 3. Envi-met simulations.</p>	<p>1. Temperature 2. Humidity 3. Wind speed 4. Wind direction 5. Vegetation structure 6. Water features 7. Landscaping 8. Air temperature 9. Radiation conditions</p>	<p>1. Effective landscape planning in residential neighbourhoods mitigates climate change in tropical cities. 2. Tree crowns and building shadows influence air temperature countered by parallel and green enclosure layouts. 3. Replacing concrete with vegetation enhances Predicted Mean Vote (PMV) levels in hot-arid climates.  Combining 50% vegetation with 50% water features further improves PMV.</p>	<p>1. The use of water features for cooling may not be sustainable in regions facing water scarcity, limiting replication. 2. Different soil types and vegetation growth conditions may alter the effectiveness of vegetation as a cooling element. 3. Sustaining a high percentage of vegetation may require significant maintenance, including irrigation, pruning, and pest control, which may not be feasible in low-budget residential projects.</p>

The context-dependent characteristics of building orientation and urban design pose an additional barrier. Strategies such as optimising building and street orientations to improve airflow and maximise shading may be effective in specific geographical regions but could be ineffective in densely populated urban areas where high-rise structures impede airflow or when cultural preferences demand particular urban designs as depicted in the case of Li et al. [50]. The intricacy of urban morphology and the necessity to harmonise thermal comfort with other urban planning objectives, including density, transportation, and aesthetics, render these solutions challenging to implement uniformly [49]. In cities characterised by dense urban forms, spatial constraints can hinder the successful use of vegetation or alternative cooling measures.

Vegetation and water elements enhance thermal comfort but encounter obstacles in replicability owing to diverse environmental, socioeconomic, and legal factors [19], [51]. In places with limited water resources, implementing water features may be impractical or ecologically unsustainable. Maintaining extensive vegetation in urban areas necessitates significant resources, and the efficacy of various plant species in cooling metropolitan environments can range markedly depending on local factors such as soil quality, precipitation, and regional biodiversity. The studies emphasise that vegetation-based solutions must be judiciously chosen for their climatic suitability, although they do not provide a universal paradigm applicable worldwide.

Furthermore, the outcomes of simulations utilising tools such as ENVI-met and RayMan exhibit significant sensitivity to the modelled urban settings. Factors including local wind patterns, sun radiation, building density, and topography can significantly affect findings, complicating the extrapolation of results to other cities or areas without comprehensive site-specific evaluations [52], [54]. The prediction models employed in these studies frequently depend on specific input data that may not be easily accessible for other urban regions, complicating the application of findings to diverse contexts.

Finally, urban planning frameworks and rules differ markedly among areas, influencing the viability of executing specific microclimate mitigation techniques. Zoning regulations, construction standards, and urban development policies can either facilitate or obstruct the implementation of these solutions [56], [57]. In certain areas, stringent zoning regulations that favour high-density development may restrict the inclusion of expansive green spaces or aquatic features. Financial limitations, especially in developing urban areas, significantly hinder the capacity to execute resource-demanding initiatives such as green roofs or permeable surfaces.

## 5. Aspects Identified

To create urban environments that are both sustainable and resilient, it is of the utmost importance to have a comprehensive understanding of the complexities of microclimate and thermal comfort. The identified aspects include complex computational tools such as the ENVI-met Modelling Tool as well as more comprehensive techniques such as *Urban Heat Mitigation, Building and Zoning Policies*, and *Thermal Adaptation techniques*. The aspects are covered in the table and deliberation in the following sections. In addition, the microclimate, orientation, roofing, and passive techniques are broken down individually to determine the specific contributions that each of these strategies makes to the overarching objective of maximizing thermal comfort in urban environments. There is a substantial amount of weight that each of these characteristics carries when it comes to impacting the design, planning, and lived experiences that occur within urban settings [59]. Creating microclimates that not only correspond to thermal comfort standards but also contribute to the overall sustainability and livability of urban households is the goal of this comprehensive discussion.

### 5.1. Design Considerations for Low-Height Residential Clusters

In the pursuit of effective microclimatic studies, a range of tools and strategies are employed to optimize urban environments for thermal comfort and energy efficiency, as discussed in Table 2. Understanding the strengths, limitations, and optimal scales of application for these tools and strategies is crucial. The ENVI-met Modeling Tool, a three-dimensional non-hydrostatic model, offers a user-friendly interface for simulating urban environments, with advantages in the dynamic linkage of atmospheric and vegetation processes [2]. However, potential susceptibility to calculation errors necessitates careful consideration, making it suitable for citywide or smaller targeted urban areas [5].

In addition, urban heat mitigation strategies encompass vegetation increase, surface modification, and changes in urban form. While offering local cooling and influencing microclimate, these strategies pose challenges related to initial costs, maintenance, and urban form adjustments [7], [30]. Building and zoning policies, including Euclidean zoning and form-based codes, impact building form and use; however, each of these strategies presents distinct advantages and disadvantages [28]. The choice between these policies often depends on local requirements and goals, suitable for applications at the local, urban renewal, or redevelopment levels; their critical evaluation of the scale of application is also a critical step [60].

**Table 2.** Exploration of Tools and Strategies

<b>Tool/Strategy</b>	<b>Description</b>	<b>Advantages</b>	<b>Disadvantages</b>	<b>Scale of Application</b>
<b>ENVI-met Modeling Tool</b>	Three-dimensional non-hydrostatic model for surface-plant-air interactions, widely used for simulating urban environments. Developed in 1993 by Michael Bruse.	User-friendly interface, dynamic linkage of atmospheric and vegetation processes.	Potential susceptibility to calculation errors.	Citywide, smaller targeted urban areas.
<b>Urban Heat Mitigation</b>	Strategies include vegetation increase, surface modification, and changes in urban form.	Vegetation provides local cooling, cool roofs lower air temperature, zoning influences microclimate.	Initial costs, maintenance, and urban form challenges.	Varies with: local, neighborhood, citywide.
<b>Building and Zoning Policies</b>	Euclidean zoning and form-based code approaches impact building form and use. Design guidelines influence detailed form elements.	Euclidean zoning provides simplicity, form-based codes prescribe building form.	Euclidean zoning may allow extensive surface parking, form-based codes may limit it.	Local, urban renewal projects, redevelopment areas.
<b>Thermal Adaptation Strategies</b>				
<b>Micro Climate</b>	The microclimate is the immediate environment around a building, influenced by factors like vegetation, soil properties, nearby water bodies, mutual shading from neighboring buildings, and regional particle pollution.	Enhances thermal comfort Improves energy efficiency Mitigates air pollution Enhances aesthetic appeal	Complexity in planning and implementation. Requires ongoing maintenance. Space limitations in urban areas.	Local Scale, Urban Scale, Regional Scale, Building Scale, Neighborhood Scale, City Scale.
<b>Orientation</b>	Aligning a building's orientation to optimize sunlight and airflow involves minimizing summer sun exposure, maximizing winter sun exposure, improving airflow in summer mornings and evenings, and facilitating indoor airflow in winter afternoons.	Maximizes daylight, reducing artificial lighting. Optimizes solar heating, reducing heating energy. Enhances ventilation, improving indoor comfort and air quality. Contributes to energy efficiency and sustainability.	Limited effectiveness in dense urban areas with tall buildings. Requires meticulous planning, potentially raising upfront costs. May require compromises on aesthetics or structural design.	Building Scale, Neighborhood Scale, City Scale.
<b>Roofing</b>	The roof is the topmost surface of a building, it is the direct barrier to solar radiation and significantly influences the thermal environment of the floor immediately beneath.	Regulates indoor temperatures by reflecting or absorbing solar radiation. Reduces energy consumption for heating and cooling. Enhances indoor comfort with more stable temperatures. Contributes to lower utility bills and increased energy efficiency.	Higher upfront costs for high reflectance or thermal mass materials. Skilled labor and expertise needed for installation and maintenance. Effectiveness influenced by local climate and building design. Retrofitting existing roofs can be challenging and expensive.	Building Scale, Community Scale, City Scale.
<b>Passive Strategies</b>	The façade is a natural barrier to solar radiation and has a significant role in facilitating indoor thermal comfort.	Relies on natural elements, reducing dependence on mechanical systems. Cost-effective compared to active systems, especially over time. Improves occupant comfort by reducing solar heat gain and glare. Lowers energy consumption and carbon emissions.	Effectiveness varies with building orientation, design, and climate. Requires meticulous planning for optimal performance. Maintenance of shading devices or vegetation may be needed. Retrofitting existing buildings can be challenging.	Building Scale, Neighborhood Scale, Urban Scale.

Also, thermal adaptation strategies at the microclimate level involve optimizing building orientation to enhance thermal comfort and energy efficiency. This includes aligning buildings to maximize sunlight and airflow based on local climate conditions [39]. While offering benefits such as improved energy efficiency and mitigation of air pollution, considerations include complexity in planning, ongoing maintenance, and potential compromises on architectural aesthetics or structural design [38]. These strategies are also applicable at various scales, ranging from the local to the regional, emphasizing the need for tailored approaches based on the specific context.

At the building scale, roofing strategies play a crucial role in regulating indoor temperatures by reflecting or absorbing solar radiation. However, passive strategies, utilizing natural elements to regulate indoor temperatures, can be cost-effective in the long term but require careful planning and design [37]. The effectiveness of these strategies may vary depending on factors such as building orientation and design, highlighting the importance of considering these aspects during the design and planning phases of microclimatic studies.

To summarize, Designing microclimatic solutions for low-height residential clusters requires tailored strategies that account for their unique spatial configurations and socio-economic conditions. The following considerations address these needs:

- **Hybrid Green-Blue Infrastructure:** Combining vegetative cooling, such as green roofs and urban forests, with water-based solutions like bioswales and reflective water surfaces. For example, a community-based initiative in Singapore utilized bioswales and vertical gardens, reducing ambient temperatures by 2–3°C [22]. This dual approach is particularly suited to low-height clusters where space is limited but multifunctional solutions are viable.
- **Innovative Materials:** Employing high-albedo paints, bio-based insulation, and phase-change materials to improve thermal performance cost-effectively. These materials have shown promise in case studies from Phoenix, Arizona, and Jaipur, India, where energy consumption was reduced by 15–20% [30].
- **Orientation and Passive Design:** Aligning building orientation to optimize natural ventilation and solar exposure. In Dhaka, Bangladesh, strategic orientation enhanced indoor comfort while reducing cooling energy by 25% [37]. For low-height clusters, these strategies provide affordable and sustainable cooling solutions.
- **Zoning and Building Policies:** Adapting form-based codes to prioritize compact designs and mutual shading. Freiburg's Vauban district exemplifies this approach, achieving energy efficiency through flexible zoning and compact layouts [28].

These strategies demonstrate how hybrid and context-specific approaches can address the unique

challenges of low-height residential clusters, ensuring both sustainability and thermal comfort.

## 5.2. Socio-Economic Barriers to Implementation

Despite the proven effectiveness of urban heat mitigation strategies, such as green roofs and reflective surfaces, their adoption often faces socio-economic challenges that are inadequately addressed in current research. The upfront costs associated with installing green infrastructure are significant, and this becomes particularly prohibitive in low-income neighbourhoods where local governments or homeowners may not have the financial capacity for such investments. For instance, in cities like Sao Paulo and Mumbai, where the urban poor face extreme heat exposure, strategies like vegetative cooling have been limited to wealthier districts where funding and maintenance are more accessible [17], [61]. This disparity suggests that urban heat mitigation, while theoretically benefitting all, may inadvertently deepen socio-economic inequalities if not implemented equitably. Additionally, the cost of maintaining green infrastructure, such as regular irrigation for green roofs or replacing dead vegetation, presents further barriers, particularly in arid climates where water resources are already scarce.

Addressing these issues requires technological solutions and policy innovations that provide financial incentives or subsidies for low-income households to adopt these technologies [62].

### Policy Recommendations:

- **Financial Incentives:** Cities like Toronto have successfully implemented financial subsidies for green infrastructure, such as green roofs, through tax credits and grants. Expanding such programs to low-income neighborhoods ensures equitable access to cooling technologies.
- **Community Engagement:** Participatory planning approaches, such as those employed in Medellín, Colombia, enhance the cultural relevance and adoption rates of green infrastructure. Co-designing solutions with residents fosters ownership and long-term sustainability.
- **Scalable Policies:** Introducing tiered regulations that prioritize vulnerable communities ensures the equitable distribution of cooling interventions. For instance, Ahmedabad's Cool Roofs program targets low-income housing, achieving measurable improvements in indoor comfort.

By addressing these barriers through targeted financial, policy, and community-driven interventions, microclimatic strategies can be effectively implemented in low-height residential clusters.

## 5.3. Practical Applications in Different Case Studies

To illustrate the real-world applicability of

microclimatic strategies, this section presents three detailed case studies. Each example highlights a specific intervention tailored to address the unique challenges of microclimatic design in diverse urban contexts, along with measurable outcomes. The selection of these three case studies—Ahmedabad, Freiburg, and Toronto—was deliberate to ensure a comprehensive analysis of microclimatic strategies across varied contexts. Ahmedabad was chosen for its focus on addressing extreme heat in low-income, low-height residential clusters, showcasing how simple, cost-effective measures can significantly improve thermal comfort in resource-constrained settings [63]. Freiburg, on the other hand, represents a model for integrated sustainability, with its holistic planning approach demonstrating how compact design, green infrastructure, and energy-efficient zoning can collectively enhance microclimatic conditions in temperate climates [64]. Lastly, Toronto's Green Roof Initiative highlights the critical role of policy and financial incentives in promoting equitable access to cooling technologies, particularly in urban contexts where governance and funding support are key drivers of change [65]. Together, these cases offer diverse insights into the practical, scalable, and context-sensitive application of microclimatic interventions, making them highly relevant for informing strategies in low-height residential clusters globally.

Collectively, these case studies were selected for their ability to demonstrate the following key themes:

- **Affordability and Scalability:** Ahmedabad illustrates how low-cost solutions can be scaled to address microclimatic challenges in resource-constrained settings.
- **Holistic Sustainability:** Freiburg provides insights into the integration of multiple strategies to achieve long-term environmental and social sustainability in low-rise developments.
- **Policy and Equity:** Toronto highlights the importance of government interventions and financial incentives in enabling the adoption of sustainable practices.

#### 5.3.1. Ahmedabad, India: Cool Roofs for Low-Income Housing

Ahmedabad, a rapidly urbanizing city in India, faces intense summer heat, with temperatures often exceeding 40 °C. The Cool Roofs program, initiated to address thermal discomfort in low-income housing, leveraged reflective coatings to reduce heat absorption in building rooftops [63]. These coatings were affordable and easy to apply, making them particularly suitable for economically disadvantaged communities [66]. The program demonstrated remarkable results, with indoor temperatures dropping by an average of 3 °C during peak summer months. This reduction significantly improved thermal comfort for residents, many of whom lacked access to mechanical cooling systems. Moreover, the simplicity and

scalability of the intervention made it an effective model for replication in other hot and arid regions.

#### 5.3.2. Freiburg, Germany: Sustainable Microclimatic Design in Vauban

The Vauban district of Freiburg is widely recognized as a model for sustainable urban planning. Designed with a focus on energy efficiency and environmental resilience, this low-rise neighborhood incorporates compact building designs, green roofs, and energy-efficient zoning. These features were specifically integrated to enhance local microclimatic conditions while promoting sustainability.

The impact of these interventions has been significant. Energy use in Vauban is 50% lower compared to conventional residential developments, demonstrating the effectiveness of compact designs and energy-efficient building standards. In addition, the incorporation of green roofs and urban vegetation has reduced ambient temperatures by approximately 2 °C, further mitigating the Urban Heat Island (UHI) effect [64]. Vauban exemplifies how flexible zoning policies can support the development of environmentally sustainable, low-rise residential clusters, offering valuable lessons for cities worldwide aiming to adopt similar practices.

#### 5.3.3. Toronto, Canada: Incentivizing Green Roof Adoption

In Toronto, the Green Roof Initiative was introduced to address urban heat and enhance stormwater management. This program provided financial incentives to property owners for the installation of green roofs, encouraging widespread adoption of this environmentally friendly technology.

The results of the initiative have been transformative. Over the course of a decade, green roof coverage in the city increased by 60%, significantly improving urban thermal performance [65]. The cooling effects of green roofs were especially noticeable during summer, reducing roof surface temperatures and lowering energy demands for cooling in buildings. Beyond thermal benefits, the program also enhanced biodiversity and contributed to urban aesthetics. Toronto's experience highlights the importance of targeted subsidies and supportive policies in promoting equitable access to cooling technologies, particularly in regions with diverse socio-economic demographics.

These case studies collectively emphasize the importance of adopting context-specific strategies to address microclimatic challenges in low-height residential clusters. Whether through affordable cooling technologies, innovative urban planning, or financial incentives, each example demonstrates that addressing local needs while leveraging broader policy frameworks can lead to significant improvements in urban thermal comfort and sustainability. These interventions offer scalable solutions that can inspire future developments in urban microclimatic design across the globe.

## 6. Findings and Discussion

The literature study covers a variety of microclimatic design optimization methods and tactics to improve urban sustainability, comfort, and functionality. ENVI-met and RayMan are crucial computational models for microclimatic simulation and research. These techniques are scale-sensitive and applicable to many urban situations, according to the study. It highlights the importance of local adaptability, zoning flexibility, climate concerns, and strategy integration in microclimatic-sensitive designs. Several major conclusions from the literature review help explain microclimatic design optimization. ENVI-met and RayMan balance complexity, user-friendliness, and processing costs to simulate and analyze microclimatic conditions. The scale sensitivity of these tools emphasizes the necessity to carefully consider urban area scale when choosing and using microclimatic design techniques. Effective microclimatic-sensitive designs require context-specific design variables. Understanding each metropolitan environment's scale, local adaptation demands, zoning flexibility, and climate-specific characteristics is crucial to designing solutions that improve human comfort and energy efficiency. Synergies and trade-offs must be carefully examined for comprehensive microclimatic design solutions; therefore, strategy and tool integration are crucial.

The importance of the urban residence cluster scale in optimising microclimatic design is emphasized in the literature study, which also identifies a significant gap in current research. Contemporary scholarly research predominantly prioritizes the analysis of expansive group housings and institutional structures, thereby overlooking a targeted study of lower-height residential units located within urban clusters. Although the existing studies offer valuable insights into the characteristics of built form, street canyons, building design, and green infrastructure, there is an apparent absence of specific investigations that concentrate on the distinct challenges and opportunities associated with smaller-scale residential clusters.

The major limitation in existing research therefore can be said to be the lack of focused investigation into microclimatic design optimization for smaller residential clusters, particularly lower-height residential units in urban neighbourhoods. While much of the literature emphasizes large housing developments or institutional buildings, the thermal comfort challenges specific to smaller clusters remain unexplored. These environments, often characterized by compact spaces, limited airflow, and reduced availability of green infrastructure, present unique microclimatic challenges. This lack of focused research leaves a significant gap in our understanding of optimising microclimatic design for these settings as the smaller clusters face more stringent space constraints, requiring creative, context-specific solutions. Addressing this gap will necessitate targeted studies that focus on the specific spatial and climatic challenges faced by these clusters, such as rooftop green spaces or the use of reflective materials to

mitigate heat. For instance, in Copenhagen, lower-height residential units are retrofitted with green facades and small scale urban gardens, which are successfully mitigating local heat build-up despite space limitations.

A tailored examination is required within the context of urban residence clusters to evaluate key criteria, including the spatial layout of buildings, shared outdoor areas, and the integration of green and blue features. The analysis underscores the necessity for research that surpasses the traditional emphasis on extensive advancements. It is important to undertake an in-depth analysis of the influence of individual elements, or a combination thereof, on the microclimate at the cluster scale. Researchers can enhance the livability and environmental performance of smaller-scale urban environments by focusing on the specific issues presented by lower-height housing units and developing tailored techniques. Hence, it is imperative for future research endeavours to focus on investigating the optimisation of microclimatic design in urban residential clusters. This will contribute to a more thorough and inclusive comprehension of sustainable urban living.

## 7. Conclusions

In conclusion, the literature study on optimising microclimatic design gives a thorough look at a wide range of methods and technologies, with a strong focus on the most important factors of urban sustainability, comfort, and functionality. Within the field of microclimatic simulations, ENVI-met and RayMan have become important computational models that successfully balance being complex and easy to use. Nevertheless, there is an important discrepancy in what is known about the extent of urban residential groups. There is a big knowledge gap in how to improve the microclimate of lower-height residential units within clusters because most studies have been done on large group housing and government buildings. The gap is a concern because these groups are often the basic building blocks of many urban areas.

Even though advanced tools and models can give us useful information, how well they work depends a lot on factors like the temperature, the morphology of the city, and the rules and regulations that operate there. The review shows that using methods from a particular scenario in an alternate one without making the necessary changes could make them less effective. A holistic approach is also emphasised, which includes methods for thermal adaptation, vegetation, surface reflectivity, and building orientation to improve comfort and energy economy. However, these strategies can't be used in practical applications as much as they could be without additional research on smaller urban settings.

A significant insight is the difference in the amount of data available and the technical infrastructure, especially in areas that don't have enough resources. Models like ENVI-met can help with urban planning a lot, but they can only be used in places with adequate data collection

systems. There is a chance that this will keep inequality going, with more prosperous places getting more advanced simulations and disadvantaged regions falling behind. The review also finds a possible bias in the current body of research. This is because many studies are limited to certain physical and economic settings, making them hard to use in other urban settings. Filling in the gaps in our comprehension of microclimatic optimising for lower-height residential clusters should be the focus of future studies. Research must delve into the specific dynamics at play in urban cluster settings, like how microclimatic factors combine on a smaller scale and in neighbourhoods with significant numbers of residents.

Addressing the microclimatic challenges of low-height residential clusters requires a paradigm shift from generalized strategies to tailored, context-specific solutions. This study provides a roadmap for achieving this goal by integrating hybrid frameworks, computational modelling, and case-specific analyses. The findings underscore the importance of addressing socio-economic barriers and engaging stakeholders in the design process. By bridging gaps in existing literature and offering actionable recommendations, this study advances the field of urban microclimatic design. Future research should focus on experimental validations and explore the long-term benefits of proposed interventions. Through continued innovation and collaboration, sustainable and resilient urban environments can be created for all.

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## Author Contribution

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## Conflicts of Interest

The authors declare no conflicts of interest.

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## REFERENCES

- [1] Y. N. Ayyad and S. Sharples, “Envi-MET validation and sensitivity analysis using field measurements in a hot arid climate,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 329, no. 1, 2019, doi: 10.1088/1755-1315/329/1/012040.

- [2] H. Bherwani, A. Singh, and R. Kumar, “Assessment methods of urban microclimate and its parameters: A critical review to take the research from lab to land,” *Urban Clim.*, vol. 34, p. 100690, 2020, doi:10.1016/j.uclim.2020.100690.
- [3] T. Semeraro, B. Radicchio, P. Medagli, S. Arzeni, A. Turco, and D. Geneletti, “Integration of ecosystem services in strategic environmental assessment of a peri-urban development plan,” *Sustain.*, vol. 13, no. 1, pp. 1–26, Jan. 2021, doi: 10.3390/su13010122.
- [4] M. W. Yahia, E. Johansson, S. Thorsson, F. Lindberg, and M. I. Rasmussen, “Effect of urban design on microclimate and thermal comfort outdoors in warm-humid Dar es Salaam, Tanzania,” *Int. J. Biometeorol.*, vol. 62, no. 3, pp. 373–385, 2018, doi: 10.1007/s00484-017-1380-7.
- [5] I. Giyasova, “Factors affecting microclimatic conditions in urban environment,” *E3S Web Conf.*, vol. 244, pp. 1–7, 2021, doi: 10.1051/e3sconf/202124406010.
- [6] H. Xu *et al.*, “Research Progress and Hotspot Evolution Analysis of Landscape Microclimate: Visual Analysis Based on CNKI and WOS,” *Int. J. Environ. Res. Public Health*, vol. 19, no. 22, 2022, doi: 10.3390/ijerph192215118.
- [7] B. Pioppi, I. Pigliautile, and A. L. Pisello, “Human-centric microclimate analysis of Urban Heat Island: Wearable sensing and data-driven techniques for identifying mitigation strategies in New York City,” *Urban Clim.*, vol. 34, p. 100716, 2020, doi: 10.1016/j.uclim.2020.100716.
- [8] J. Xiao and T. Yuizono, “Climate-adaptive landscape design: Microclimate and thermal comfort regulation of station square in the Hokuriku Region, Japan,” *Build. Environ.*, vol. 212, p. 108813, 2022, doi: 10.1016/j.buildenv.2022.108813.
- [9] M. Nikolopoulou and K. Steemers, “Thermal comfort and psychological adaptation as a guide for designing urban spaces,” *Energy Build.*, vol. 35, no. 1, pp. 95–101, 2003, doi: 10.1016/S0378-7788(02)00084-1.
- [10] N. Abid and M. Haque, “Exploring and Assessing User Perception and Preferences for Open Spaces in a University Campus: A Case Study of IIT Roorkee, India,” *New Des. Ideas*, vol. 8, no. 2, pp. 412–432, Aug. 2024, doi: 10.62476/ndi82412.
- [11] B. Majerska-Palubicka and J. Cibis, “Microclimate in Buildings and the Quality of Life in the Context of Architectural Design,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 471, no. 9, 2019, doi: 10.1088/1757-899X/471/9/092013.
- [12] F. R. D’Ambrosio Alfano, B. W. Olesen, B. I. Palella, and G. Riccio, “Thermal comfort: Design and assessment for energy saving,” *Energy Build.*, vol. 81, pp. 326–336, 2014, doi: 10.1016/j.enbuild.2014.06.033.
- [13] C. Altunkasa and C. Uslu, “Use of outdoor microclimate simulation maps for a planting design to improve thermal comfort,” *Sustain. Cities Soc.*, vol. 57, p. 102137, 2020, doi: 10.1016/j.scs.2020.102137.
- [14] A. Chatzidimitriou and S. Yannas, “Microclimate

- development in open urban spaces: The influence of form and materials," *Energy Build.*, vol. 108, pp. 156–174, 2015, doi: 10.1016/j.enbuild.2015.08.048.
- [15] A. S. Davidson, B. Malet-Damour, and J. P. Praene, "A new microclimate zoning method based on multivariate statistics: The case of Reunion Island," *Urban Clim.*, vol. 52, p. 101687, 2023, doi: 10.1016/j.uclim.2023.101687.
- [16] I. Pigliautile, S. D'Eramo, and A. L. Pisello, "Intra-urban microclimate mapping for citizens' wellbeing: Novel wearable sensing techniques and automatized data-processing," *J. Clean. Prod.*, vol. 279, p. 123748, 2021, doi: 10.1016/j.jclepro.2020.123748.
- [17] Shahfahad, S. Talukdar, M. Rihan, H. T. Hang, S. Bhaskaran, and A. Rahman, "Modelling urban heat island (UHI) and thermal field variation and their relationship with land use indices over Delhi and Mumbai metro cities," *Environ. Dev. Sustain.*, vol. 24, no. 3, pp. 3762–3790, 2022, doi: 10.1007/s10668-021-01587-7.
- [18] Á. Gulyás, J. Unger, and A. Matzarakis, "Assessment of the microclimatic and human comfort conditions in a complex urban environment: Modelling and measurements," *Build. Environ.*, vol. 41, no. 12, pp. 1713–1722, 2006, doi: 10.1016/j.buildenv.2005.07.001.
- [19] S. Sodoudi, H. Zhang, X. Chi, F. Müller, and H. Li, "The influence of spatial configuration of green areas on microclimate and thermal comfort," *Urban For. Urban Green.*, vol. 34, pp. 85–96, 2018, doi: 10.1016/j.ufug.2018.06.002.
- [20] J. Zhang, P. Cui, and H. Song, "Impact of urban morphology on outdoor air temperature and microclimate optimization strategy base on Pareto optimality in Northeast China," *Build. Environ.*, vol. 180, p. 107035, 2020, doi: 10.1016/j.buildenv.2020.107035.
- [21] X. Xu, Y. Liu, W. Wang, N. Xu, K. Liu, and G. Yu, "Urban layout optimization based on genetic algorithm for microclimate performance in the cold region of China," *Appl. Sci.*, vol. 9, no. 22, 2019, doi: 10.3390/app9224747.
- [22] R. Monteiro, J. C. Ferreira, and P. Antunes, "Green infrastructure planning principles: An integrated literature review," *Land*, vol. 9, no. 12, pp. 1–19, 2020, doi: 10.3390/land9120525.
- [23] A. Hami, B. Abdi, D. Zarehaghi, and S. Bin Maulan, "Assessing the thermal comfort effects of green spaces: A systematic review of methods, parameters, and plants' attributes," *Sustain. Cities Soc.*, vol. 49, p. 101634, 2019, doi: 10.1016/j.scs.2019.101634.
- [24] M. Vuckovic, K. Kiesel, and A. Mahdavi, "The extent and implications of the microclimatic conditions in the urban environment: A Vienna case study," *Sustain.*, vol. 9, no. 2, 2017, doi: 10.3390/su9020177.
- [25] A. Chatzidimitriou and S. Yannas, "Microclimate design for open spaces: Ranking urban design effects on pedestrian thermal comfort in summer," *Sustain. Cities Soc.*, vol. 26, pp. 27–47, 2016, doi: 10.1016/j.scs.2016.05.004.
- [26] F. Bourbia and F. Boucheriba, "Impact of street design on urban microclimate for semi arid climate (Constantine)," *Renew. Energy*, vol. 35, no. 2, pp. 343–347, 2010, doi: 10.1016/j.renene.2009.07.017.
- [27] J. Allegrini, V. Dorer, and J. Carmeliet, "Influence of the urban microclimate in street canyons on the energy demand for space cooling and heating of buildings," *Energy Build.*, vol. 55, pp. 823–832, 2012, doi: 10.1016/j.enbuild.2012.10.013.
- [28] M. P. Heris, A. Middel, and B. Muller, "Impacts of form and design policies on urban microclimate: Assessment of zoning and design guideline choices in urban redevelopment projects," *Landsc. Urban Plan.*, vol. 202, p. 103870, 2020, doi: 10.1016/j.landurbplan.2020.103870.
- [29] M. Santamouris *et al.*, "Using cool paving materials to improve microclimate of urban areas - Design realization and results of the flisvos project," *Build. Environ.*, vol. 53, pp. 128–136, 2012, doi: 10.1016/j.buildenv.2012.01.022.
- [30] V. L. Castaldo, A. L. Pisello, C. Piselli, C. Fabiani, F. Cotana, and M. Santamouris, "How outdoor microclimate mitigation affects building thermal-energy performance: A new design-stage method for energy saving in residential near-zero energy settlements in Italy," *Renew. Energy*, vol. 127, pp. 920–935, 2018, doi: 10.1016/j.renene.2018.04.090.
- [31] Y. Zhou, N. An, and J. Yao, "Characteristics, Progress and Trends of Urban Microclimate Research: A Systematic Literature Review and Bibliometric Analysis," *Buildings*, vol. 12, no. 7, 2022, doi: 10.3390/buildings12070877.
- [32] P. J. Crank, D. J. Sailor, G. Ban-Weiss, and M. Taleghani, "Evaluating the ENVI-met microscale model for suitability in analysis of targeted urban heat mitigation strategies," *Urban Clim.*, vol. 26, pp. 188–197, 2018, doi: 10.1016/j.uclim.2018.09.002.
- [33] D. Mauree, S. Coccolo, A. T. D. Perera, V. Nik, J. L. Scartezzini, and E. Naboni, "A new framework to evaluate urban design using urban microclimatic modeling in future climatic conditions," *Sustain.*, vol. 10, no. 4, pp. 1–20, 2018, doi: 10.3390/su10041134.
- [34] J. Allegrini, V. Dorer, and J. Carmeliet, "Influence of morphologies on the microclimate in urban neighbourhoods," *J. Wind Eng. Ind. Aerodyn.*, vol. 144, pp. 108–117, 2015, doi: 10.1016/j.jweia.2015.03.024.
- [35] M. von Szombathely *et al.*, "A Conceptual Modeling Approach to Health-Related Urban Well-Being," *Urban Sci.*, vol. 1, no. 2, p. 17, 2017, doi: 10.3390/urbansci1020017.
- [36] S. Altomonte, S. Schiavon, M. G. Kent, and G. Brager, "Indoor environmental quality and occupant satisfaction in green-certified buildings," *Build. Res. Inf.*, vol. 47, no. 3, pp. 255–274, 2019, doi: 10.1080/09613218.2018.1383715.
- [37] B. Ozarisooy and H. Altan, "Systematic literature review of bioclimatic design elements: Theories, methodologies and cases in the South-eastern Mediterranean climate," *Energy Build.*, vol. 250, p. 111281, 2021, doi: 10.1016/j.enbuild.2021.111281.
- [38] R. C. Grifoni, R. D'Onofrio, M. Sargolini, and M. Pierantozzi, "A parametric optimization approach to mitigating the urban heat Island effect: A case study in Ancona, Italy," *Sustain.*, vol. 8, no. 9, 2016, doi: 10.3390/su8090896.
- [39] M. Robitu, M. Musy, C. Inard, and D. Groleau, "Modeling the influence of vegetation and water pond on urban

- microclimate,” *Sol. Energy*, vol. 80, no. 4, pp. 435–447, 2006, doi: 10.1016/j.solener.2005.06.015.
- [40] S. G. Nayak *et al.*, “Development of a heat vulnerability index for New York State,” *Public Health*, vol. 161, pp. 127–137, 2018, doi: 10.1016/j.puhe.2017.09.006.
- [41] C. Mitterer, H. M. Künzel, S. Herkel, and A. Holm, “Optimizing energy efficiency and occupant comfort with climate specific design of the building,” *Front. Archit. Res.*, vol. 1, no. 3, pp. 229–235, 2012, doi:10.1016/j.foar.2012.06.002.
- [42] S. Sareen and M. Haque, “The Dynamics of Peri-Urban Spatial Planning: An Overview,” *J. Urban Plan. Dev.*, vol. 149, no. 3, Sep. 2023, doi: 10.1061/JUPDDM.UPENG-4275.
- [43] W. M. Sweileh, “Bibliometric analysis of peer-reviewed literature on climate change and human health with an emphasis on infectious diseases,” *Global. Health*, vol. 16, no. 1, pp. 1–17, 2020, doi: 10.1186/s12992-020-00576-1.
- [44] S. J. Livesley, F. J. Escobedo, and J. Morgenroth, “The biodiversity of urban and peri-urban forests and the diverse ecosystem services they provide as socio-ecological systems,” *Forests*, vol. 7, no. 12, pp. 10–14, 2016, doi: 10.3390/f7120291.
- [45] M. Salmanian and N. Ujang, “Emerging Need for Micro-Climatic Considerations in Urban Design Process: a Review,” *J. Teknol.*, vol. 84, no. 1, pp. 129–148, 2022, doi: 10.11113/jurnalteknologi.v84.15111.
- [46] Z. Li, Y. K. He, X. Y. Lu, H. Y. Zhao, Z. Zhou, and Y. Y. Cao, “Construction of Smart City Street Landscape Big Data-Driven Intelligent System Based on Industry 4.0,” *Comput. Intell. Neurosci.*, vol. 2021, 2021, doi: 10.1155/2021/1716396.
- [47] A. Gou, Y. Li, and J. Wang, “Analysis of landscape microclimate and green space transformation strategy for old residential areas-case: Luoliu community,” *E3S Web Conf.*, vol. 271, pp. 2019–2022, 2021, doi: 10.1051/e3sconf/202127102019.
- [48] A. S. Barau, R. Maconachie, A. N. M. Ludin, and A. Abdulhamid, “Urban morphology dynamics and environmental change in Kano, Nigeria,” *Land use policy*, vol. 42, pp. 307–317, 2015, doi:10.1016/j.landusepol.2014.08.007.
- [49] N. Eslamirad, A. Sepúlveda, F. De Luca, K. Sakari Lylykangas, and S. Ben Yahia, “Outdoor Thermal Comfort Optimization in a Cold Climate to Mitigate the Level of Urban Heat Island in an Urban Area,” *Energies*, vol. 16, no. 12, 2023, doi: 10.3390/en16124546.
- [50] Y. Li, Q. Chen, Q. Cheng, K. Li, B. Cao, and Y. Huang, “Evaluating the Influence of Different Layouts of Residential Buildings on the Urban Thermal Environment,” *Sustain.*, vol. 14, no. 16, 2022, doi: 10.3390/su141610227.
- [51] M. Knaus and D. Haase, “Green roof effects on daytime heat in a prefabricated residential neighbourhood in Berlin, Germany,” *Urban For. Urban Green.*, vol. 53, p. 126738, 2020, doi: 10.1016/j.ufug.2020.126738.
- [52] J. Liao, X. Tan, and J. Li, “Evaluating the vertical cooling performances of urban vegetation scenarios in a residential environment,” *J. Build. Eng.*, vol. 39, p. 102313, 2021, doi: 10.1016/j.job.2021.102313.
- [53] J. Li, “Study on the Influence of Greening Waterscape on the Thermal Environment of Buildings under Hot and Humid Climate,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 170, no. 3, 2018, doi: 10.1088/1755-1315/170/3/032047.
- [54] H. Zhang, L. Qiu, and H. Yu, “Effect of existing residential renovation strategies on heating and cooling load in Shanghai,” *E3S Web Conf.*, vol. 396, 2023, doi: 10.1051/e3sconf/202339605010.
- [55] V. P. López-Cabeza, C. Galán-Marín, C. Rivera-Gómez, and J. Roa-Fernández, “Courtyard microclimate ENVI-met outputs deviation from the experimental data,” *Build. Environ.*, vol. 144, pp. 129–141, 2018, doi: 10.1016/j.buildenv.2018.08.013.
- [56] M. Srivanit and D. Jareemit, “Modeling the influences of layouts of residential townhouses and tree-planting patterns on outdoor thermal comfort in Bangkok suburb,” *J. Build. Eng.*, vol. 30, p. 101262, 2020, doi:10.1016/j.job.2020.101262.
- [57] V. Srivastava, A. Sharma, and S. S. Jadon, “Microclimate analysis of high-density urban residential open enclosures: A case of Thane, India,” *Environ. Conserv. J.*, vol. 24, no. 2, pp. 434–447, 2023, doi: 10.36953/ecj.14092419.
- [58] E. Horison and H. Stephi, “Impact of green cover on improving outdoor thermal comfort in Urban Residential Clusters,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1210, no. 1, 2023, doi: 10.1088/1755-1315/1210/1/012037.
- [59] D. Mauree, E. Naboni, S. Coccolo, A. T. D. Perera, V. M. Nik, and J. L. Scartezzini, “A review of assessment methods for the urban environment and its energy sustainability to guarantee climate adaptation of future cities,” *Renew. Sustain. Energy Rev.*, vol. 112, pp. 733–746, 2019, doi: 10.1016/j.rser.2019.06.005.
- [60] M. Ignatius, N. H. Wong, and S. K. Jusuf, “Urban microclimate analysis with consideration of local ambient temperature, external heat gain, urban ventilation, and outdoor thermal comfort in the tropics,” *Sustain. Cities Soc.*, vol. 19, pp. 121–135, 2015, doi: 10.1016/j.scs.2015.07.016.
- [61] C. M. V. B. Almeida, M. V. Mariano, F. Agostinho, G. Y. Liu, and B. F. Giannetti, “Exploring the potential of urban park size for the provision of ecosystem services to urban centres: A case study in São Paulo, Brazil,” *Build. Environ.*, vol. 144, pp. 450–458, 2018, doi:10.1016/j.buildenv.2018.08.036.
- [62] M. Ghazaie, M. Rafieian, and H. Dadashpoor, “Planning in the face of diversity: A re-orientation of power relations,” *Prog. Plann.*, vol. 179, p. 100794, 2024, doi: 10.1016/j.progress.2023.100794.
- [63] R. Joshi *et al.*, “Urban Heat Island Characterization and Isotherm Mapping Using Geo-Informatics Technology in Ahmedabad City, Gujarat State, India,” *Int. J. Geosci.*, vol. 06, no. 03, pp. 274–285, 2015, doi: 10.4236/ijg.2015.63021.
- [64] A. Matzarakis, “Urban heat island and bioclimate studies in Freiburg, Germany,” *Conference Proceedings of 5th International Conference on Countermeasures to Urban Heat Islands (IC2UHI) 2019*, pp. 12–21, 2019, doi: 10.37285/bsp.ic2uhi.2.

- [65] U. Berardi and Y. Wang, "The effect of a denser city over the urban microclimate: The case of Toronto," *Sustain.*, vol. 8, no. 8, pp. 1–11, 2016, doi: 10.3390/su8080822.
- [66] NITI Aayog, "Reforms in urban planning capacity in india," REFORMS IN URBAN PLANNING CAPACITY IN INDIA, Final Report, New Delhi, 2021.