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Review

Outdoor Thermal Comfort Research and Its Implications for Landscape Architecture: A Systematic Review

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Abstract: Amid global warming and urbanization, outdoor thermal comfort has become a critical consideration in landscape architecture. This study integrates a systematic review and bibliometric analysis of 1417 empirical studies (1980–2024) sourced from Web of Science, aiming to clarify the current state of research, identify core themes, and propose future directions. This study examines key evaluation models, the influence of spatial morphology, and their practical applications using keyword co-occurrence, citation networks, and thematic analyses. Findings show a significant rise in research over the past decade, particularly in tropical and subtropical regions. Core themes include thermal comfort indices (PMV, PET, and UTCI), microclimate regulation, and important spatial indicators (height-to-width ratio, sky view factor, and greening). The field is increasingly shifting towards simulation tools (such as ENVI-met and CFD) rather than traditional field measurements, with artificial intelligence emerging as a tool for predictive and regulatory purposes, though its application remains limited. However, much of the research focuses on small-scale morphological optimization and lacks a systematic framework for spatial representation. Future research should prioritize developing a comprehensive evaluation system adaptable to diverse landscapes, investigating the interplay between spatial form and thermal comfort, and advancing sustainable, low-carbon design strategies. The insights from this study provide a solid foundation for improving outdoor thermal comfort and guiding sustainable urban development through landscape architecture.

Keywords: outdoor thermal comfort; landscape architecture; spatial morphology; bibliometric analysis; sustainable landscape design

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1. Introduction

Outdoor thermal comfort is a crucial aspect of landscape architecture, particularly in the context of urbanization and climate change [1]. As urban areas continue to expand, the effects of global warming and urban heat islands are becoming increasingly evident, highlighting the importance of creating spaces that are comfortable, sustainable, and resilient to changing environmental conditions [2]. Global warming and the associated rise in urban temperatures exacerbate the challenges faced by outdoor spaces, making it imperative to understand how landscape architecture can contribute to mitigating these effects. Urbanization further complicates this issue by altering natural landscapes, reducing green spaces, and increasing the demand for urban infrastructure that can intensify heat stress [3].

The relationship between outdoor thermal comfort and landscape architecture is multifaceted, as various design elements, such as vegetation, materials, spatial configurations, and microclimatic conditions, play a critical role in shaping human comfort in outdoor environments. Outdoor thermal comfort refers to the state in which individuals feel neither too hot nor too cold in outdoor spaces, and it is influenced by several factors, including ambient temperature, humidity, solar radiation, and wind speed [4–6]. Research has shown that landscape architects can actively improve outdoor thermal comfort by integrating design solutions such as green roofs, urban parks, water features, and tree canopies to reduce the urban heat island effect and improve overall environmental quality [7–11].

However, despite the growing recognition of the importance of outdoor thermal comfort in urban design, there is a lack of comprehensive research that bridges the gap between thermal comfort studies and landscape architecture practices. Most studies on outdoor thermal comfort focus on bioclimatic models and environmental psychology [12,13], often neglecting the critical role that landscape architects play in shaping outdoor spaces. This gap in the literature leaves a need for further exploration of how specific landscape features and design elements impact thermal comfort in outdoor spaces.

This study aims to address this gap by focusing on the specific relationship between outdoor thermal comfort and landscape architecture. The research explores how various landscape elements, such as spatial form, vegetation, and microclimate regulation, influence outdoor comfort in urban settings. By integrating quantitative analysis with qualitative insights, this study seeks to provide actionable recommendations for landscape architects and urban planners to design more comfortable and sustainable public spaces.

2. Research Methodology

This study comprehensively reviews and analyzes the body of literature on outdoor thermal comfort within the discipline of landscape architecture using both a qualitative review and bibliometric analysis. The methodology follows the PRISMA guidelines for systematic reviews to ensure transparency, rigor, and reproducibility in the review process [14]. Below, we provide a detailed explanation of each component of the methodology.

2.1. Data Sources and Literature Retrieval

The bibliographic data were primarily obtained from the Web of Science Core Collection, which indexes high-quality academic journals and conference proceedings globally. We selected this database due to its comprehensive coverage of the relevant academic fields and its rigorous indexing standards. To ensure representativeness and academic credibility, the literature retrieval strategy was structured as follows:

Primary Keywords: "outdoor thermal comfort", "outdoor human thermal comfort", "outdoor thermal perception", and "outdoor thermal stress".

Logical Operators: relevant terms and synonyms were connected using the 'OR' operator.

Time Frame: the search spanned from 1980 to 1 December 2024, ensuring the inclusion of historical developments and the latest research outcomes.

Document Type: only empirical journal articles were included, while reviews, conference papers, book chapters, and other document types were excluded.

An initial search resulted in 1733 documents, which were further refined through a two-step screening process, as outlined below. This process is in compliance with the PRISMA checklist (Supplementary Materials) and helps ensure the systematic and unbiased inclusion of studies.

2.2. Literature Screening and Quality Control

The literature screening process was conducted in two rounds:

1. Initial Screening: Titles and abstracts were reviewed to exclude irrelevant documents, non-academic publications, and studies outside the scope of the review. A total of 110 reports were excluded in this round;
2. FullText Screening: The remaining studies were reviewed for quality and eligibility. Only articles with rigorous empirical methods were included. Reports were excluded if they were found to have methodological issues (36 studies) or were deemed irrelevant to the main topic (75 studies).

In total, 1417 studies were retained for bibliometric analysis and qualitative review. All steps adhered to the PRISMA guidelines to ensure compliance with systematic review standards.

2.3. Qualitative Literature Review

The qualitative review provides an in-depth summary of the significant theories, research progress, and methodological approaches to outdoor thermal comfort in landscape architecture. The section is divided into the following parts:

1. Summary of Core Theories and Models

This part highlights the major models used to assess thermal comfort in outdoor environments, including PMV (Predicted Mean Vote), PET (Physiological Equivalent Temperature), and UTCI (Universal Thermal Climate Index). These models are examined in the context of their application to landscape architecture, focusing on their effectiveness in different climatic conditions, especially in urban environments.

2. Research Method Comparison

This section contrasts different research methodologies used in the field, such as field measurements, laboratory-controlled experiments, and simulation-based methods. The strengths and limitations of each approach are discussed, particularly their suitability for assessing thermal comfort in outdoor spaces with various environmental and spatial configurations. Simulation methods, particularly CFD (Computational Fluid Dynamics) and Energy Balance Models, are explored in depth given their increasing application in landscape architecture.

3. Spatial Morphology and Thermal Comfort

This component emphasizes how spatial design factors such as sky view factor (SVF), height-to-width ratio (H/W), and vegetation influence outdoor thermal comfort. It provides a comprehensive review of studies that explore the interaction between urban form and microclimate, underscoring how spatial morphology can either mitigate or exacerbate thermal discomfort in public spaces.

2.4. Bibliometric Analysis Methods

The bibliometric analysis used in this study aims to uncover research trends, identify hotspots, and recognize key studies that have shaped the field of outdoor thermal comfort. The analysis was conducted using the bibliometrix 4.1.4 R package, following these methods [15]:

1. Analysis of Research Output

We examine the annual publication trends to identify key milestones and shifts in the research field. This analysis highlights the rapid increase in outdoor thermal comfort studies over the past decade and indicates significant geographical concentration in tropical and subtropical regions.

2. Keyword Co-Occurrence and Research Hotspots

A co-occurrence network of keywords was constructed to reveal the dominant research topics and methodological frameworks. This method allows us to identify the key themes such as thermal comfort indices, microclimate regulation, and spatial morphology, as well as their evolution over time.

3. Citation Analysis and Core Literature

Citation and co-citation analyses were used to map the field's knowledge structure and identify influential studies and authors. The citation network provides insights into the interconnectedness of research topics and helps pinpoint the foundational works that have significantly impacted the development of the field.

4. Research Theme Evolution

We tracked the evolution of research themes over time by examining the temporal distribution of keywords. This analysis reveals emerging trends, such as the increasing integration of simulation tools like ENVI-met and CFD models in thermal comfort studies, as well as the growing role of artificial intelligence in predictive modeling for outdoor spaces.

2.5. Compliance with PRISMA Guidelines

The systematic review adhered to PRISMA 2020 guidelines for transparency and reproducibility. The review process, including literature screening and selection, is clearly illustrated in the PRISMA flow diagram (Figure 1). This diagram outlines the study selection process and the number of studies included at each stage.

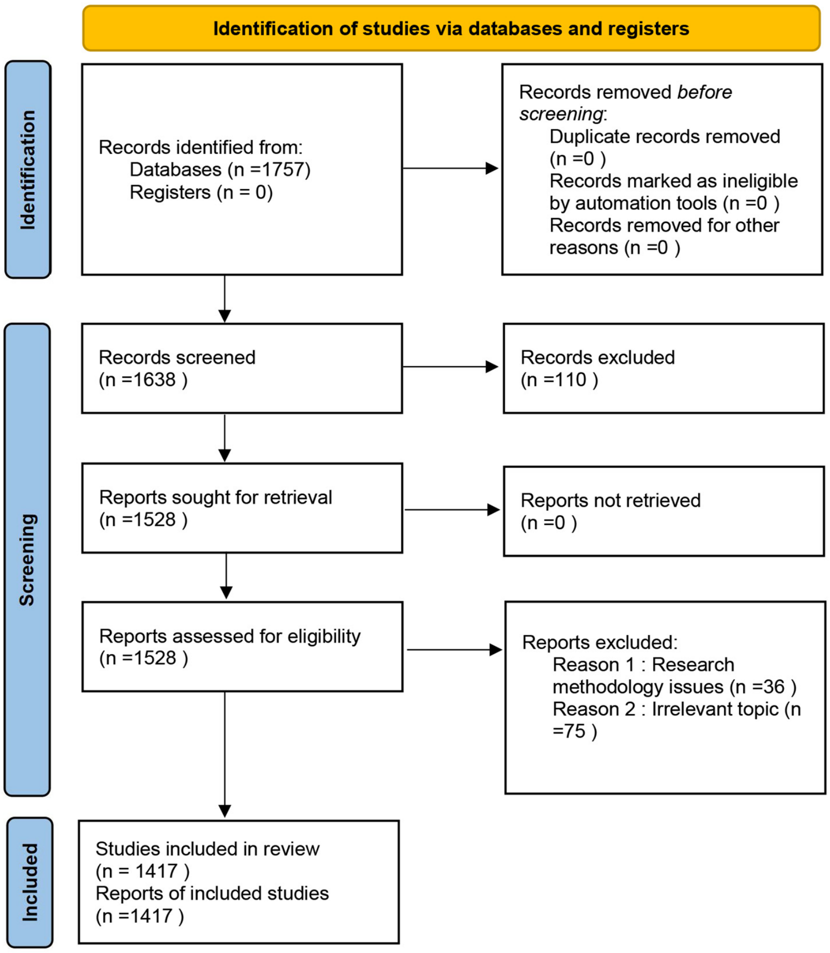

Figure 1. PRISMA flow diagram: literature screening and selection process.

No formal registration of this systematic review was conducted, as it focuses on a literature review and bibliometric analysis rather than a clinical or intervention-based study. However, we encourage future researchers to consider registration when conducting similar reviews involving experimental interventions.

Although the risk of bias assessment is a common practice in systematic reviews, we did not perform it for the studies included in this review. The primary reason is that the reviewed studies were largely observational and diverse in their methodologies, making a uniform risk of bias assessment challenging. Given the focus on empirical studies rather than clinical trials or intervention studies, performing such an assessment was deemed less applicable.

2.6. Summary of Research Methods

By combining systematic bibliometric analysis with qualitative review, this study provides a comprehensive overview of the research status and trends in outdoor thermal comfort within landscape architecture. Bibliometric analysis uses visualization tools to identify research hotspots and academic networks, while a qualitative review offers deeper insights into theoretical models and methodologies. Together, these approaches highlight significant advancements, existing gaps, and practical guidance for future research, enabling the field to address the challenges posed by climate change and urbanization effectively.

3. Thermal Comfort Evaluation Indicator System

3.1. Physical Environment Factors

From the very beginning of thermal comfort research, researchers have sought to define the effects of the environment on people by means of quantitative environmental indicators. Modern thermal comfort research began in 1919 at the Pittsburgh Laboratory of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) with the study of the effects of indoor climate on human thermal comfort. As the research progressed and was refined, researchers gradually refined the criteria and incorporated parameters such as air movement velocity, thermal radiation, and air humidity. In 1923, FC Hpoughten and Yaglou et al. introduced the effective temperature (ET) indicator, which has had a profound impact on thermal comfort research [16]. This set of indicators combines air temperature, humidity, and wind speed in different ways so that the same value of effective temperature gives the same thermal sensation. In 1932, Vernon and Warner enhanced the consideration of radiation to the effective temperature and used the black sphere temperature (corrected for the wet sphere temperature) to calculate the corrected effective temperature (CET) [17]. A large number of World War II studies on the training efficiency of military forces under thermal environmental exposure were able to carry out the post-war concept of thermal stress, which is still heavily borrowed and utilized in subsequent studies. In 1957, the U.S. Navy, in an effort to assess the thermal exposure of U.S. Marine Corps recruits in training, proposed the wet bulb globe temperature (WBGT) index [18]. In 1959, Thorn of the U.S. National Weather Service proposed the Discomfort Index (DI), in which the formula reflects the effect of hot and humid summer climatic conditions on the degree of human discomfort through the combination of dry bulb and wet bulb temperatures [19], and it was applied to the U.S. summer comfort and hours of work forecasting. The wind chill index (WCI) proposed by Siple in 1945 [20] and the new wind chill equivalent temperature (WCET), based on the modification related to heat loss from exposed skin, which has been adopted by the U.S. National Weather Service since 2001 [21], are representatives of empirical models applied to comfort in cold environments.

Thermal comfort evaluation indicators based on physical factors of the environment have been gradually abandoned by medical and architectural fields due to the lack of consideration of human factors. However, the simplicity also implies the convenience of calculation and high adaptation, and it is still used by meteorology, urban and rural planning, and other disciplines.

3.2. Human Stationary Modeling

With the continuous deepening of the research, academics have gradually realized that, in addition to external meteorological factors, human perception of the thermal environment is often affected by a variety of physiological and psychological factors of the human body itself at the same time. Thermal comfort is the subjective feeling of human beings under the influence of external environmental conditions, and there are general individual differences in thermal perception of the external environment. Different individuals' gender, age, metabolic rate, clothing thermal resistance [22], cultural background and other factors will have an impact on the perception of thermal comfort under the same environmental conditions, and so these factors have also been included in the thermal comfort evaluation indicators system.

In the 1960s, a large number of thermal comfort models were proposed to integrate several parameters, the most representative of which are the PMV steady state model proposed by Fanger and the two-node base heat transfer model by Gagge. Most of the subsequent typical thermal comfort models have been developed on this basis.

The first classical thermal comfort model was the predicted mean vote (PMV) model based on Fanger's human heat balance equation [23]. It transformed the study of thermal comfort from qualitative to quantitative research.

The PMV thermal comfort model was proposed by Fanger in the 1970s, through a large number of climate chamber experimental research, to meet the human body comfortable state of the three conditions and, based on this, to establish a mathematical formula related to thermal comfort. Furthermore, it integrated the human body's thermal comfort of the four physical variables (air temperature, flow velocity, the average radiation temperature of the environmental surface, and the relative humidity) and the two anthropogenic variables (clothing thermal resistance and the human body activity), variables proposed to be able to predict the PMV indicator. The theoretical basis for the construction of the PMV indicator is that the human body is considered to be at a comfortable temperature when it is close to thermal neutrality, and the greater the thermal load on the human body, the further the human body deviates from the state of thermal comfort under a certain thermal humidity condition. This indicator represents the thermal sensation of the majority of people in the same environment. Since this index does not represent the thermal sensation of all people, Fanger proposed the predicted percentage of dissatisfied (PPD) index as a supplement. The PPD index represents the percentage of the population that is dissatisfied with the thermal environment and is expressed in terms of probability. Therefore, the PMV model is widely used to evaluate the thermal comfort of the human body indoors. PMV is still widely used in practice as the basis of the ISO 7730 [24] and ASHRAE 55 standards [25].

In 2002, Fanger et al. extended the original PMV evaluation index by proposing a PMV index for different countries (or regions) and climate zones, which was calculated by multiplying the original PMV index by a correction factor ranging from 0.5 to 1.0 [26].

The characteristics of the stationary model of the human body determine that the PMV model is more suitable for the evaluation of thermal comfort in scenarios where the external climatic conditions are relatively constant and the amount of human movement is small. As the PMV is still the most frequently used thermal comfort evaluation system in indoor scenarios. Outdoor thermal environments are far more complex than indoor environments, and in the outdoors, the diversity of activities is significantly increased, metabolic levels are more varied, and different individuals are dressed differently, which makes the evaluation of outdoor thermal comfort more difficult.

3.3. Human Non-Stationary Modeling

Gagge of the Pierce Institute at Yale University, USA, proposed the "two-node model", which divides the human body into a core layer and a skin surface layer, and it consists of two subsystems: the controlling system and the controlled system. The two-node model also uses the heat balance method to predict thermal comfort, but with a non-stationary state assumption [22].

In 1971, Gagge et al. introduced the concept of skin wetness on the basis of the effective temperature index; then, they proposed the new effective temperature ET* [27], but ET* is only applicable to the environment of light clothing, low activity level, and low wind speed. After that, Gonzalez et al. proposed the standard effective temperature (SET) [28] in 1974 by considering different activity levels and the thermal resistance of clothing, thus expanding the use of ET*.

On the basis of the two-node model, Höppe proposed the Munich human body heat balance model (MEMI) in 1984 [29], which assumes that the heat in the human body is brought to the skin surface through blood circulation, and this value is equal to the human body's sensory heat dissipation. Therefore, on the basis of the human body heat balance equations, we add the two heat transfer equations from the human body's core to the skin as well as from the skin surface to the surface of the garment to derive the surface temperature of the garment, the surface temperature of the skin, as well as the temperature of the human body's core, which are the three important indexes of the human body's thermal sensation, and then predict the human body's thermal sensation [30].

Based on the MEMI, Höppe et al. in 1999 constructed the Physiological Equivalent Temperature (PET) index specifically for the evaluation of comfort in outdoor thermal environments, which is defined as the air temperature at which the human body's heat gain and loss in a typical indoor environment (without wind and solar radiation) equilibrates with the same core and skin temperatures under the complex outdoor conditions to be evaluated [31]. It is defined as the air temperature at which the heat balance of the human body in a typical indoor environment (without wind and solar radiation) is in equilibrium with the core and skin temperatures of the same complex outdoor conditions to be evaluated [32]. This indicator takes the influence of the main meteorological parameters, such as activity, clothing, and individual parameters, on comfort into account. Compared to the PMV model, it is more comprehensive and in-depth, as it considers the influence of various factors. The PET metric has been heavily used in evaluations and studies related to outdoor environments.

Based on Gagge's two-node heat transfer model of the human core and surface skin, a three-node model of the human core + skin + clothing and even more complex multi-node models have been developed, which abstract the human body into multiple parts, each of which is divided into layers of skin, fat, muscle, bone, etc. Each part is considered to be a heat transfer node with thermal physiological parameters and is governed by the energy conservation equation. Each layer of each part is considered to be a heat transfer node with thermal physiological parameters controlled by energy and mass conservation equations. Some of the more common multi-node models include the Tanabe model [33], the Fiala model [34], the Berkeley model [35], etc. These models are more commonly used in the fields of medical care, design of protective clothing, and design of air-conditioning systems for transportation.

The advantage of this type of model is that it provides a clearer analysis of the internal heat conduction in the human body, which is conducive to a more detailed understanding of the perceived thermal comfort of the human body. This type of model is more suitable for physiologically relevant thermal comfort studies and is also valuable for specific individuals such as athletes, industrial workers, or people suffering from diseases.

Multidisciplinary cross-fertilization has led to the mature development of thermal physiology and heat exchange theories. The Universal Thermal Climate Index (UTCI), which combines Fiala's multi-node thermal physiology model and the adaptive dressing model [36], has been established [37]. Blazejczyk et al. found that the correlation between UTCI and commonly used comfort indices, such as PMV, ET*, SET, PET, etc., is up to 96% or more; however, the UTCI is more sensitive to temporal changes in meteorological elements than other comfort indices and can well reflect the nuances of the human body when it feels the weather changes [38]. Its characteristics are applicable to multi-climatic and complex climatic conditions, and it shows higher accuracy when compared with several outdoor thermal comfort indices, and accordingly, the calculation process is more complicated.

The evaluation indicators of outdoor thermal comfort vary from one thermal comfort indicator to another, and the evaluation of the same thermal comfort indicator varies from one season to another in the same region, which implies that it is of great importance to carry out on-site validation before the evaluation. The first issue in evaluating thermal comfort under different environmental conditions is to select appropriate outdoor thermal comfort indicators. In the past decades, hundreds of thermal comfort indicators have been developed, and according to incomplete statistics, as of 2017, no less than 165 thermal comfort models have been proposed [39], but they are limited to the constraints of different disciplines, as they focus on the differences, the cost of validation, the influence of dissemination, etc. The most commonly used research indicators are mainly concentrated in a limited number of PMV, PET, SET, and UTCI. Also, the selection of outdoor thermal comfort indicators is important for the evaluation of different environmental conditions. The selection of outdoor thermal comfort indicators has also become a major research direction in outdoor thermal comfort research.

From the published literature, it indicated that the modified PMV, PET, and UTCI are the mainstream thermal comfort evaluation criteria in landscape architecture research and practice.

4. Outdoor Thermal Environment Parameter Acquisition Method

4.1. On-Site Field Measurements

The first and most intuitive research method is to analyze the relevant data through the measurement of field climatic data, which can obtain the first-hand meteorological data through the thermometer, anemometer, weather station, and other equipment, as well as carry out the subsequent evaluation work. Due to the convenience and accuracy of field measurements, this parameter acquisition method is still adopted by a large number of research institutes [40–42].

Concurrently, due to the spatial and temporal homogeneity, many studies can observe and analyze the behaviors of the people in the environment while carrying out on-site measurements [43,44]. It can also conveniently take the form of questionnaires or scores in the way of supplementing the study so as to reach the coupling study of objective data and subjective feelings of the human body [41,45–47]. After calculating PET, UTCI, and other criteria from meteorological data measured in the field, correlation studies can also be conducted with data such as thermal sensation vote (TSV) and thermal comfort vote (TCV) [48–51]. This type of research method is also the most widely used in field measurement research.

With the development of information technology in recent years, studies have also gradually begun to conduct correlation analyses with the help of network data, such as social media network evaluations, cell phone signaling of people in the vicinity, and other data [32,52,53], as a way to strengthen the credibility of the study.

In addition to this, field measurements are an important means of verifying the accuracy and feasibility of other research methods and have been used as an adjunct in a large number of studies. The accuracy of the simulation software and the associated evaluation model can be tested and calibrated by comparing the results of field measurements and pre-experiments prior to the start of formal experiments [54–57].

Although the field measurement method has the advantages of being intuitive, accurate, and easy to obtain data, it still has major limitations. First, it is more rigorous in terms of the location and time of the study. Second, it is difficult to fully comply with the expectations of the experimental design when the experiments are carried out under uncontrollable meteorological conditions. Third, the study can only be satisfied with the situation of a certain area and cannot accurately predict the future situation.

4.2. Laboratory-Controlled Experiments

In response to the shortcomings of the field measurement research methodology described in the previous section, researchers have established laboratories to improve the conditions and efficiency of their research.

With the help of laboratory equipment, research can be carried out in a controlled or semi-controlled manner. The control of variables such as meteorological factors and spatial configurations makes it possible to conduct thermal comfort studies under specific conditions and for specific durations with a single factor.

For example, Nie et al. explored the applicability of this metric for the assessment of outdoor thermal comfort in cold and bitterly cold winter regions in Tianjin, China. Through a series of analyzing, the results concluded that the UTCI in cold regions may have ineffective compartments under its low-temperature zone through a field experiment on a campus [58]. Pigliautile et al. monitored more than 20 compartments in a full-size experimental setup in a continental Mediterranean climate. Moreover, the experiment examined evapotranspiration and analyzed high albedo surfaces numerically as a way to investigate the feasibility of mitigation strategies for the urban heat island effect [59]. Krüger et al. compared the differences in human thermal comfort perception among urban squares, streets, and canyons through laboratory simulations of thermal environments and the visualization of urban spaces [60].

Although laboratory experiments are of great value to thermal comfort research, they are generally applied to the thermal properties of materials [61–64] and are not the underpinning of outdoor thermal comfort research. These shortcomings have led to the emergence of digital simulation as a method for thermal comfort research because of the difficulties in designing experiments for these types of studies and the high cost of using them, as well as the long research period.

4.3. Digital Simulation Methods

With the burgeoning development of computer technology and the development of thermal comfort models, it has become possible to use computers to mathematically simulate those changes in the outdoor thermal environment. Numerical simulation suggests real-world phenomena by solving a set of equations related to urban climate characteristics. Currently, the main numerical methods for simulating thermal environments can be divided into two main branches: the energy balance model and Computational Fluid Dynamics.

4.3.1. Energy Balance Model (EBM)

The simulation principle of the energy balance model is to utilize the law of energy conservation at the wired nodes to obtain the values of the relevant heat quantities. It runs by calculating the energy inflows and outflows on a larger scale to solve the thermal environment and the thermal comfort level in the computational domain.

Compared to the pure CFD software, simulation programs based on the EBM, such as CitySim [65–69] and SOLWEIG [70–75], construct the model based on the main principle of energy conservation. These programs are faster and can simulate urban buildings on a larger scale; however, the simulation of airflow and heat transfer processes is more simplified. The convective effects are not directly simulated but indirectly realized by some empirical parametric equations. It is mainly used to calculate the effects of short-wave radiation on urban spaces.

The street cluster thermal time constant (CTTC) model, which is similar with the EBM principle, has also been employed in outdoor thermal comfort studies and has been used to assess the thermal effects of the built environment [76,77].

The characteristics of the model per se indicates that the energy balance model is more suitable for providing acceptable accuracy on a large scale with reasonable calculation speed. As a result, it is widely used in urban planning and other large-scale research fields. However, its significant shortcoming is the lack of consideration for the time dimension, and it is unable to measure the specific time nodes of the relevant situation at the same time. Furthermore, it cannot calculate the atmospheric movement of heat fluxes and other related values of the small-scale climate for the solution; thus, in the majority of the landscape architecture related to the research on outdoor thermal comfort, it has not been widely used.

4.3.2. Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD) simulates fluid flow by numerically solving the differential equations governing fluid dynamics. This method provides a detailed distribution of meteorological parameters in specific regions, making it highly suitable for small-scale studies and for incorporating time dimensions into thermal comfort analysis, thus improving the feasibility for assessing seasonal or temporal changes [78].

CFD simulations rely on turbulence models like the standard K-ε, RNG K-ε, and standard k-ω, which have been widely adopted in outdoor thermal comfort studies due to their computational efficiency. While a large eddy simulation (LES) has demonstrated superior accuracy in some studies, its higher computational cost limits its widespread application [79]. These turbulence models are preferred for urban simulations because they balance accuracy with manageable computational demands, making them a common choice in outdoor thermal comfort research.

In terms of software, FLUENT [80,81] and PHOENICS [82,83] are traditionally used in the built environment industry and have been validated in fields like HVAC and spacecraft design. However, their complexity limits their use in broader landscape architecture applications.

ENVI-met has emerged as a more widely utilized tool for urban microclimate simulations. Developed by Michael Bruse and his team at the University of Mainz, ENVI-met is effective in simulating interactions between solid surfaces, vegetation, and air in urban environments, making it a go-to solution for landscape architecture studies on thermal comfort [54,55,84].

In addition, Ladybug Tools, a free and open source environment plug-in based on Grasshopper, has been gradually promoted for outdoor thermal comfort research [85–92].

This review highlights that outdoor thermal comfort research within the built environment and landscape architecture remains in its exploratory stages. While theoretical tools and knowledge from related disciplines have been integrated, suitable paradigms and research frameworks tailored to landscape architecture are yet to be fully developed, necessitating further exploration in future studies.

5. Landscape Architecture for Outdoor Thermal Comfort

5.1. Research Area

Comfortable outdoor thermal environments are a common need of human beings, and studies on outdoor thermal comfort are widely distributed around the world, from Harbin, China [93], to Sydney, Australia [43], and from Baghdad, Iraq [94], to Anaba, Algeria [40]. According to the Köppen–Geiger climate classification, relevant studies have been conducted across most climatic regions, including but not limited to Af (tropical rainforest climate) [57], Cwa (subtropical winter-dry climate) [69,71], BWh (tropical desert climate) [95], Bsk (cool semi-arid climate) [58,96,97], Cfa (subtropical humid climate) [48,98], Csa (hot-summer Mediterranean climate) [99,100], and Am (tropical humid climate) [42,101–103] climate regions.

Notably, outdoor thermal comfort studies are geographically widespread but predominantly concentrated in temperate, tropical, and subtropical regions. This trend suggests that lower-latitude areas receive greater research attention due to their heightened thermal comfort challenges. Moreover, the number of studies is also related to the degree of economic development of the location, and it should be noted that there are far more studies in the more economically active regions than in the Global South, which is also something that researchers need to pay attention to.

The studies on outdoor thermal comfort also focus on the following areas, such as urban open spaces [48,51,56,84,96,104], building compounds [99,105], residential areas [106–108], urban street canyons [54,57,109,110], university campuses [41,42,97,102,111,112], etc. The thermal comfort of these areas with strong public attributes has received more attentions. In addition, there are studies conducted on archeological sites [113], traditional gardens [114], historical neighborhoods [115], botanical gardens [45], and other spaces. It is believed that in the future, with the continuous development of the research, more types of places will be included in outdoor thermal comfort studies.

5.2. Research Indicators

In the process of outdoor thermal comfort research, the selection of thermal comfort evaluation indicators is also an important portion, though the literature review highlights that WBGT [106,116,117], pmv (often need to be corrected according to the location of the climate zones) [84,94,112], SET [41,107,118–122], and other indicators have been used in relevant studies. The most widely used indicators are PET [47,57,101,108,109,123] and UTCI [55,99,103,124,125].

It is worth noting that in recent years, more and more studies have begun to try to use multiple thermal comfort study metrics together as a way to ensure the accuracy of their studies [126–133]. For example, Huang [48], Hartabela [50], Huang [49], etc., in their studies, combined PET and thermal comfort vote (TSV) control via field test calculation as a way to carry out comfort studies. Mutani [100], Zafarmandi [97], Nie [58], and others combined PET, UTCI, and PMV metrics together to determine outdoor thermal comfort, respectively, and compared the accuracy and variability of the different metrics in the same scenario, as well as gave corrections.

5.3. Indicators of Spatial Characterization

The main work of the landscape architecture discipline is oriented to outdoor spaces and forms the combination of different materials and elements. The aim of this discipline is to create a pleasant outdoor environment through the adjustment of the outdoor spatial pattern, of which outdoor thermal comfort is also a vital part.

For the above reasons, compared with the physiological and psychological indicators of the human body, thermal comfort research under the discipline of landscape architecture focuses more on the influence of environmental indicators on the small-scale thermal environment, in other words, a method to improve the four indicators of temperature, humidity, wind, and solar radiation inside the targeted site based on the form of outdoor spaces under the given external weather conditions. It indicates that outdoor thermal comfort within the framework of landscape architecture is the study of the relationship between the spatial form and the microclimate.

At the beginning of the research, researchers often analyze the climatic indicators of a particular site directly through measurement and simulation and evaluate the advantages and disadvantages of the thermal environment of the built environment [41–43,47,56,89]. With the development of the discipline, in order to make the research results more universal, and also in order to better guide the design of the practice, researchers have begun to analyze the relationship between the space form and thermal comfort. To summarize and characterize the complex and diverse spatial patterns, indicators such as the height-to-width ratio (H/W), main orientation, sky view factor (SVF), leaf area index (LAI), impervious area, etc., were introduced to quantify the characteristics of the outdoor space and to analyze the ways in which the different indicators influence the parameters of the outdoor thermal and humid environments.

For example, Wei Yang et al. [109] used ENVI-met to numerically simulate the microclimate within a street canyon. The effect of the height-to-width ratio (H/W) on outdoor thermal comfort in high-rise urban environments in Singapore was analyzed, and it was determined that H/W = 3 can be considered as a threshold for outdoor thermal comfort in Singapore. Nasrollahi et al. [105] numerically discussed the thermal performance of different configurations of traditional courtyards in the Shiraz region of Iran and concluded that the mean radiant temperature and the wind speed are the most effective parameters affecting the thermal comfort of courtyards. They suggested a high H/W ratio and a south facing configuration for better shading in summer, particularly in Iran and similar areas with comparable climatic conditions.

Xiong et al. [110] argued that the sky view factor (SVF), as one of the main morphological features reflecting the horizontal and vertical characteristics of the urban space, determines solar irradiation and wind incidence. The SVF has a great impact on thermal perception, and with the help of this metric, they revealed the mechanisms by which the microclimate and human activities affect the thermal sensation and comfort in winter.

Simulation analysis from Fahmy et al. [95] revealed the practical effect of urban trees and their actual LAI on factors such as the MRT radiant temperature. Zhang et al. [98] also concluded that the effect of vegetation on the thermal environment and ventilation depends on the tree arrangement, LAI, canopy width, and tree height.

Others have attempted to synchronize different spatial metrics into the study of the outdoor thermal environment. Shata et al. [104] measured and calculated SVF and LAI in the campus space and combined them with PET and UTCI values to confirm the importance of urban trees in modifying the microclimate of the existing university plaza.

Zhu et al. [134] determined that the correlation between H/W and air temperature was greater than the correlation between SVF and air temperature, and H/W was more effective in improving the thermal environment within an urban street canyon by combining the calculation of SVF and H/W with a thermal comfort analysis for the four locations in question.

Although there have been many attempts to tackle this issue, the questions of how to completely characterize outdoor space patterns and how to comprehensively analyze their impacts on the outdoor thermal environment have not yet been resolved. The establishment of a system of outdoor spatial morphology indicators to represent the thermal environment still requires the efforts of subsequent researchers.

5.4. Emerging Trends in Research on Artificial Intelligence (AI) Technology Applied to Outdoor Thermal Comfort

Recent advancements in artificial intelligence (AI) technologies have led to a growing body of research aimed at improving outdoor thermal comfort by leveraging machine learning, computer simulations, and intelligent control systems. AI applications in outdoor thermal comfort research encompass machine learning models, Internet of Things (IoT) technologies, and intelligent thermal comfort regulation systems, all designed to predict and optimize comfort in outdoor spaces.

1. Thermal Comfort Interpretation

AI can be utilized to interpret thermal comfort measurements, providing human-like interpretations that foster trust in decision support systems [135]. Machine learning models have been employed to assess outdoor thermal comfort in cold regions [136] and to predict thermal comfort on green sidewalks using supervised machine learning [137]. Jeong developed a data-driven approach using optimized tree-based algorithms for predicting outdoor thermal comfort and informing urban design strategies [138]. Prasad utilized AI, including machine learning tools, to assess outdoor thermal comfort using remotely sensed data (e.g., Landsat 8 imagers) for analyzing thermal comfort in metropolitan areas [139].

2. Thermal Comfort Prediction

Recent studies have demonstrated the efficacy of AI methods, such as machine learning algorithms, in predicting and enhancing thermal comfort in buildings, suggesting their potential applicability to outdoor environments as well [140]. For instance, Shahrestani et al. introduced a machine learning-based framework for predicting the impact of different urban configurations on outdoor thermal comfort by training pix2pix convolutional generative adversarial network (cGAN) models [141]. Machine learning models such as random forest (RF) and artificial neural networks (ANNs) have been used to predict various aspects of outdoor thermal comfort. Shah et al. employed the adaptive neuro fuzzy inference system (ANFIS) to determine the significant impact of air temperature on thermal comfort, leading to the development of an ANN model based solely on air temperature inputs for predicting outdoor thermal comfort [142]. Matallah utilized AI techniques for computer simulations and predicted the impact of climate change on outdoor thermal comfort in arid regions [143]. Zhang et al. comprehensively explored the assessment of macroclimate and microclimate impacts on outdoor thermal comfort using five validated ANN models [144].

3. Thermal Environment Regulation Systems

AI technologies can tailor thermal comfort solutions based on individual preferences, thereby reducing energy consumption and enhancing comfort in outdoor spaces. This personalized approach, employing sensors and intelligent systems, underscores the significance of AI in developing efficient thermal comfort systems [145]. The integration of IoT devices with AI technologies has facilitated the development of intelligent thermal comfort control systems. A smart thermal comfort control system for buildings, based on IoT and AI, demonstrates the potential of these technologies to automatically adjust living parameters to improve human comfort. The system leverages IoT hardware devices and AI algorithms to predict energy consumption and thermal comfort metrics, thereby optimizing energy use while ensuring outdoor thermal comfort [146]. Furthermore, as explored in the literature [147], urban greening can be augmented through the application of AI and IoT, mitigating the urban heat island effect and enhancing thermal comfort and walkability for pedestrians. By monitoring the thermal environment and pedestrian behavior in real time, these technologies can inform the strategic layout and maintenance of green spaces to maximize their cooling effect.

4. Accuracy and Limitations

While AI methods provide a promising avenue for improving outdoor thermal comfort, several challenges remain. The models' accuracy is contingent upon the quality of the data, the complexity of the simulation models, and the scalability of the technology to large, diverse urban environments. Models such as those based on ANNs or SVMs may be prone to overfitting if not properly validated or if trained on limited datasets. Additionally, AI models often require high computational power, which may not be accessible in resource-constrained settings, limiting their widespread adoption.

The integration of AI technologies into outdoor thermal comfort in landscape spaces represents an emerging research area with significant potential to improve urban livability. Through predictive modeling, personalized comfort systems, and intelligent design, AI technologies could revolutionize the approach to thermal comfort in outdoor environments. Future research directions may focus on further refining AI models to enhance accuracy and efficiency and exploring innovative applications that integrate esthetic considerations with environmental comfort.

6. Review of Existing Research

The current state of research on outdoor thermal comfort within the context of landscape architecture cannot be fully understood through traditional qualitative review methods alone. This chapter integrates both bibliometric analyses and qualitative reviews to offer a systematic overview of the field, focusing on the developmental stages, thematic evolution, and future directions of research. The figures presented in this chapter clearly illustrate research trends, hot topics, and methodological advancements in the field.

6.1. Development Trends in Thermal Comfort Research

Outdoor thermal comfort has become a central interdisciplinary research focus, as it is driven by the escalating impacts of global climate change and urbanization. The bibliometric analysis of annual scientific publications (Figure 2) shows that the number of studies remained relatively modest from 2000 to 2013, with fewer than 50 papers published each year. However, the number of publications surged significantly after 2013, coinciding with the intensification of climate change and urbanization. This increase in research output highlights the growing academic attention to outdoor thermal comfort as a crucial strategy for improving urban thermal environments.

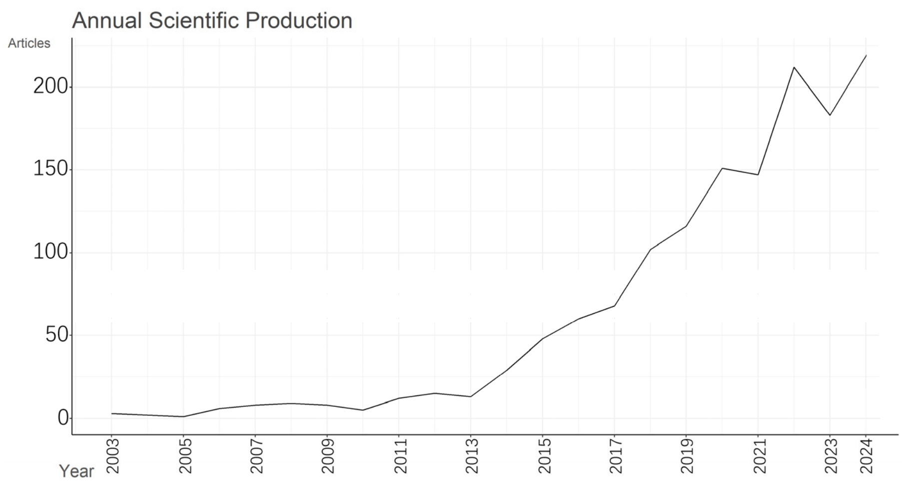

Figure 2. Annual trends in the number of publications on outdoor thermal comfort (2003–2024).

The temporal distribution of keyword frequencies (Figure 3) further reveals the evolution of research priorities over time. Early studies focused on basic topics such as 'urban ventilation' and 'adaptation', followed by 'PET' and 'design for adaptation'. Afterwards, the use of quantitative evaluation methods such as "PET" (Physiological Equivalent Temperature) and "UTCI" (Universal Thermal Climate Index) has increased significantly, demonstrating a gradual shift towards data-driven approaches.

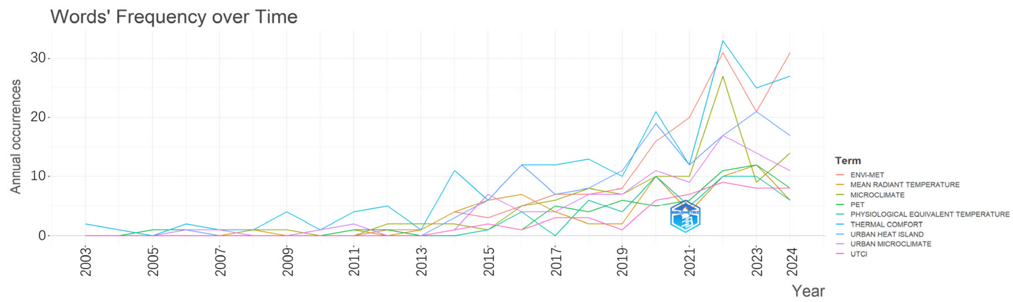

Figure 3. Temporal distribution of keywords in outdoor thermal comfort research.

6.2. Research Hotspots and Keywords Co-Occur

The keyword co-occurrence network (Figure 4) illustrates the distribution of research themes, with a focus on terms like temperature, environment, and microclimate. Keywords such as spaces and vegetation are densely clustered, indicating that studies not only address the physical characteristics of thermal environments but also emphasize spatial design strategies for microclimate regulation. This integrated approach reflects the growing recognition of landscape architecture's role in managing outdoor thermal comfort.

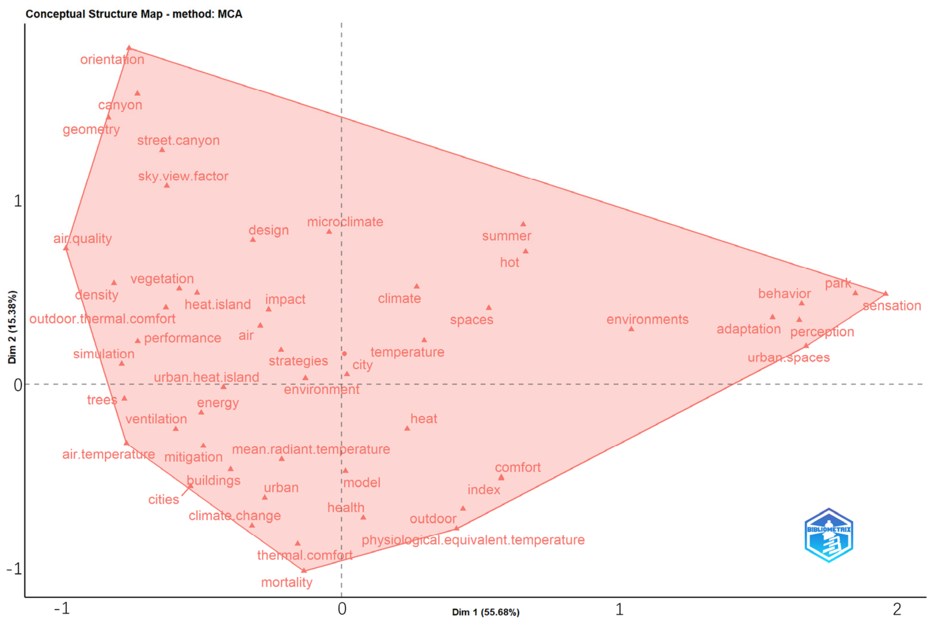

Figure 4. Keyword co-occurrence network: research themes and focus areas. The axes represent keywords (on the horizontal axis) and their frequency of co-occurrence (on the vertical axis). This visualization highlights how certain keywords, such as thermal comfort and vegetation, are closely related, signifying the interconnectedness of these concepts within the literature.

The thematic structure map (Figure 5) reveals the relationships among different keywords. For example, spatial features like "street canyon" and "sky view factor" are closely related to "thermal comfort". This association reflects the tendency of researchers to incorporate quantitative indicators of the spatial form into the design of microclimate regulation when analyzing thermal environments.

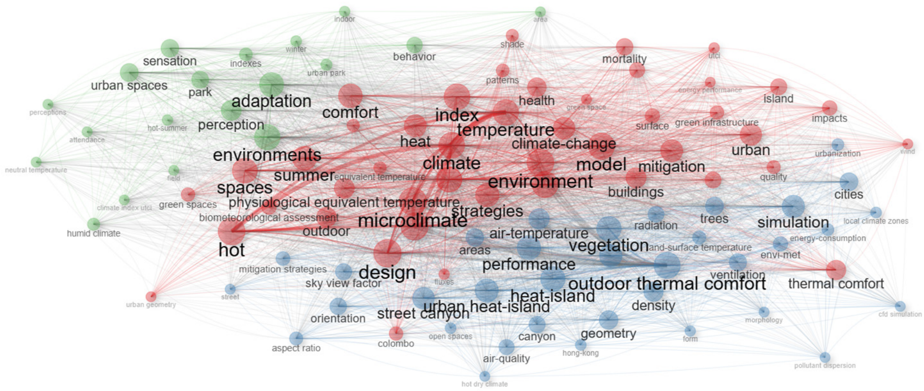

Figure 5. Thematic structure and keyword relationships in outdoor thermal comfort research. The color-coded map represents thematic clusters in the research, such as thermal comfort, microclimate, and design strategies. The varying colors of the clusters indicate different thematic groups, with overlapping themes reflecting an interdisciplinary approach to the topic, involving both environmental and design aspects.

6.3. Evolution of Thermal Comfort Evaluation Models

As shown in the tree map of the keyword distribution (Figure 6), thermal comfort evaluation models have evolved significantly. The PMV model is useful for indoor settings but is less applicable in complex outdoor environments. The PET model has gained popularity due to its flexibility, especially in the context of climate change, and the UTCI model has become mainstream since 2019 for its applicability in outdoor environments. Additionally, hybrid models combining meteorological data with socio-economic parameters are emerging, indicating a shift towards multidimensional evaluations.

Figure 6. Tree map of keyword distribution in outdoor thermal comfort research. The size of each box represents the relative frequency of each keyword in recent publications. Larger boxes indicate that a term has been more frequently used, highlighting key topics and research trends in the field of outdoor thermal comfort. Keywords like PET, microclimate, and urban heat islands are central to current research.

6.4. Shifts in Research Methodology and Technological Evolution

Research methods have undergone a significant shift, moving from field measurements to computer simulations. As shown in Figure 7, keywords related to simulation tools like ENVI-met and CFD have gained prominence since 2015. Early studies relied heavily on high-precision weather station data, but these methods had limitations in terms of spatial coverage and time constraints. The widespread adoption of simulation techniques has improved the efficiency and accuracy of studies, enabling larger-scale analysis and offering insights into spatial morphology (Figure 3). However, as indicated in Figure 7, CFD simulations have continued to grow, but the accuracy of these tools can be limited by input data quality and model validation against field measurements.

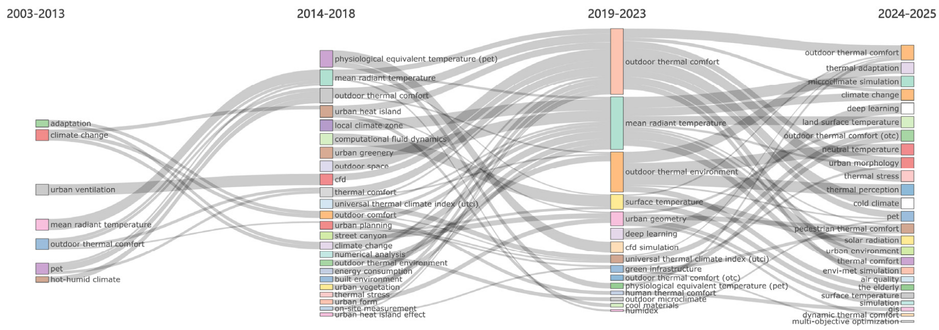

Figure 7. Evolution of research methods and application of simulation techniques. This figure tracks the usage of simulation methods like CFD, ENVI-met, and PET over time. The bars represent the number of studies using each method within specified time frames.

These tools are capable of assessing the effectiveness of design strategies at various scales. As illustrated in the thematic structure (Figure 5), “simulation” and “model” are centrally positioned within the study, alongside “temperature” and “environment”, highlighting the pivotal role of simulation in analyzing the thermal environment. Furthermore, “simulation” and “model” are associated not only with meteorological parameters but also with “street canyon” and “green spaces”. This suggests that researchers are increasingly utilizing simulation techniques to explore the influence of spatial patterns on the thermal environment and to propose more effective design optimization strategies.

6.5. Keyword Evolution and Future Trends

Combining the keyword theme evolution map (Figure 7) and the theme trend map (Figure 8) clearly illustrates the dynamic evolution of outdoor thermal comfort research. These shifts indicate not only changes in scientific approaches but also the adaptation of landscape architecture to emerging challenges such as climate change and urbanization.

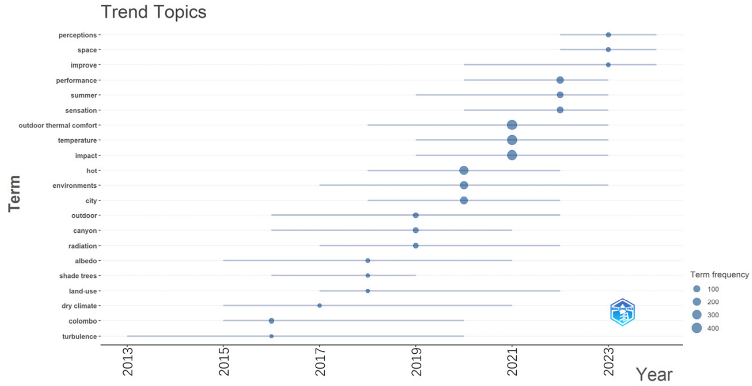

Figure 8. Thematic evolution of keywords in outdoor thermal comfort research (2013–2024).

1. Early Focus (2003–2013)

During the early years of research, the emphasis was on basic concepts such as adaptation to climate, urban ventilation, and general studies on human comfort in outdoor environments. These early studies primarily focused on the relationship between human physiology and environmental parameters, with an emphasis on thermal sensation and microclimate factors.

2. Emerging Models and Evaluation Methods (2014–2018)

As interest in outdoor thermal comfort grew, the focus shifted towards more specific models for evaluation. Keywords like PET (Physiological Equivalent Temperature) and UTCI (Universal Thermal Climate Index) gained prominence, signifying the development of more sophisticated and context-specific thermal comfort models. This period saw the increased use of computational methods and simulations to account for complex outdoor environments. This shift allowed researchers to integrate more variables such as solar radiation and wind speed in thermal comfort evaluations.

3. Technological Advancements and Simulation (2019–2023)

From 2019 onwards, the landscape of research on outdoor thermal comfort expanded to include technological advancements like simulation tools, Computational Fluid Dynamics (CFD), and deep learning algorithms. The focus on spatial morphology, including the role of vegetation, urban heat islands, and microclimate, became central to studies. The relationship between landscape architecture and thermal comfort was further explored through these advanced methodologies, enabling better predictive models and more accurate simulations of human comfort in urban spaces.

4. Future Trends (2024 and Beyond)

Looking ahead, real-time monitoring, multi-objective optimization, and artificial intelligence are expected to play significant roles in advancing the study of outdoor thermal comfort. Research is likely to focus on dynamic thermal comfort models that adapt in real-time to changing environmental conditions and human activities. Additionally, there will be increased emphasis on the integration of AI-powered tools for personalized comfort solutions and real-time microclimate adjustments in urban landscapes.

These evolving trends point to a future where landscape architecture can more effectively contribute to climate adaptation through intelligent design and advanced computational methods, enabling urban spaces to better accommodate human thermal comfort.

6.6. Synthesis: Impact of Spatial Morphology on Outdoor Thermal Comfort

A key outcome of this study is the recognition that spatial morphology plays a critical role in regulating outdoor thermal comfort. Landscape architecture, by integrating spatial design elements such as street canyons, green spaces, and vegetation patterns, significantly influences the microclimate and thereby impacts human comfort in urban environments. The use of simulation techniques has allowed researchers to quantify these effects and evaluate the effectiveness of different landscape designs in mitigating urban heat islands and enhancing thermal comfort.

Research has shown that spatial configurations, such as the orientation of buildings, the density of green spaces, and the design of urban canyons, affect how heat is distributed and how air flows in urban environments. These factors directly influence the urban heat island effect and thermal comfort. For instance, green roofs and urban trees can provide shade and cooling, reducing the effects of excessive heat during hot weather and improving overall comfort levels.

This study also highlights the growing importance of digital simulation in evaluating the role of spatial morphology in outdoor thermal comfort. As the field of landscape architecture becomes more integrated with advanced computational models, researchers are able to assess the impact of spatial factors more accurately and in real-time. Future research should continue to explore how landscape elements can be optimized through modeling and simulation to improve thermal comfort in response to climate change and urban expansion.

7. Discussion

7.1. Thermal Comfort and Landscape Architecture: A Pathway to Better Outdoor Environments

Landscape architecture plays a critical role in enhancing outdoor thermal comfort by integrating natural elements with human-built spaces. In the face of climate change and urbanization, thermal comfort has become a central concern in the field of landscape architecture. Landscape architects are uniquely positioned to mitigate the effects of urban heat islands and improve outdoor thermal comfort through the careful consideration of spatial morphology, including building layouts, vegetation arrangement, and the design of water features and shading systems.

With rising global temperatures, particularly in urban areas where the urban heat island effect exacerbates heat exposure, the role of landscape architects becomes even more essential. Through optimized landscape design, urban areas can be transformed into more comfortable spaces for outdoor activities, helping to reduce the impacts of extreme temperatures. Therefore, incorporating thermal comfort research into landscape architecture is a powerful strategy for addressing the challenges posed by climate change while simultaneously improving urban living conditions.

This growing body of research underscores the importance of integrating green infrastructure into urban landscapes. The strategic placement of vegetation and water features can significantly lower local temperatures, provide shade, and contribute to evaporative cooling, all of which enhance outdoor thermal comfort. Moreover, shading and wind patterns have been shown to influence the thermal comfort of urban public spaces, and landscape architects must consider these factors when designing public areas [148,149].

7.2. The Role of Spatial Morphological Characteristics

Spatial morphological characteristics play a decisive role in outdoor thermal comfort. Factors such as building density, vegetation distribution, urban canyons, and shading systems all directly influence microclimates and thermal comfort levels. By thoughtfully designing urban spaces with attention to green spaces, water features, and the orientation of structures, landscape architects can effectively mitigate the urban heat island effect and enhance comfort in outdoor spaces.

Particularly in densely built environments, landscape architects can reduce heat exposure by strategically designing open spaces, increasing green infrastructure, and introducing water features to create more comfortable microclimates. Furthermore, urban canyons, green coverage, and building orientation all play key roles in regulating airflow and heat accumulation, influencing the overall thermal environment in cities [150].

It is clear that landscape architects, by leveraging spatial morphology, can directly influence the microclimate, thereby enhancing the overall thermal comfort in urban spaces. Thus, the effective integration of green infrastructure, water bodies, and shading systems into urban design plays a critical role in addressing climate change challenges and improving the comfort of outdoor environments [151].

7.3. The Practical Significance of Thermal Comfort Research for Landscape Architecture

Thermal comfort research provides valuable theoretical and practical guidance for landscape architects. By incorporating thermal comfort indices such as PMV, PET, and UTCI, landscape architects can more accurately assess the impact of spatial designs on thermal comfort. The application of simulation technologies, such as Computational Fluid Dynamics (CFD) and ENVI-met, enables landscape architects to model various design scenarios and evaluate how different urban configurations affect thermal conditions.

Moreover, thermal comfort research highlights the importance of incorporating shading, green infrastructure, and ventilation into design strategies. The integration of these elements not only improves thermal comfort but also enhances climate resilience. For instance, green roofs, vertical gardens, and reflective surfaces have proven effective in mitigating thermal discomfort, particularly in hot urban environments. These insights provide landscape architects with actionable strategies for creating climate-adaptive urban spaces that promote human well-being [152,153].

7.4. Key Directions for Future Research

The future of landscape architecture and thermal comfort research lies in the integration of dynamic adaptive design strategies and multi-scale evaluation systems. These approaches will address the complexities of climate change and urbanization, ensuring that landscape designs remain effective in the face of changing environmental conditions. Key directions for future research include the following:

1. Development of Multi-Scale Integrated Evaluation Systems

Comprehensive frameworks that integrate regional and local scales are essential for understanding the impacts of climate change and meeting specific design needs. By integrating microclimate analysis, researchers can offer more holistic insights into mitigating outdoor heat stress, which is crucial for landscape design [154].

2. Dynamic Adaptive Design

Advancing the ability to design for thermal comfort through real-time climate data and dynamic modeling technologies is critical. Future research should explore adaptive design strategies that focus on optimizing vegetation and water bodies to enhance adaptability to fluctuating environmental conditions [155].

3. Low-Carbon and Ecological Design

In alignment with global sustainability goals, future studies should prioritize low-carbon materials, nature-based solutions, and green technologies. These strategies should aim to balance energy efficiency with ecological benefits to create sustainable urban environments [156].

The strategic integration of green spaces can reduce urban heat islands while aligning with low-carbon strategies to enhance both thermal comfort and ecological sustainability.

4. Cultural and Behavioral Research

Thermal comfort perceptions vary across different cultural and behavioral contexts. Future research should explore these differences to develop spatial designs that cater to diverse urban populations, enhancing inclusivity and functionality [157].

5. Technological Integration and Interdisciplinary Collaboration

The application of artificial intelligence, big data, and IoT technologies will deepen our understanding of thermal comfort and provide actionable insights for urban planning. Interdisciplinary collaboration will be essential to drive innovation in this field [158].

By addressing these critical directions, thermal comfort research can more effectively respond to the challenges of climate change and urbanization, contributing to sustainable, inclusive, and equitable urban development.

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References

1. Kong, D.; Gu, X.; Li, J.; Ren, G.; Liu, J. Contributions of Global Warming and Urbanization to the Intensification of Human-Perceived Heatwaves over China. *J. Geophys. Res. Atmos.* **2020**, *125*, e2019JD032175. [CrossRef]
2. Wang, Y.; Zhao, N.; Yin, X.; Wu, C.; Chen, M.; Jiao, Y.; Yue, T. Global Future Population Exposure to Heatwaves. *Environ. Int.* **2023**, *178*, 108049. [CrossRef] [PubMed]
3. Guo, Y.; Ren, Z.; Dong, Y.; Hu, N.; Wang, C.; Zhang, P.; Jia, G.; He, X. Strengthening of Surface Urban Heat Island Effect Driven Primarily by Urban Size Under Rapid Urbanization: National Evidence from China. *GISci. Remote Sens.* **2022**, *59*, 2127–2143. [CrossRef]
4. Yan, Y.; Xu, Y.; Yue, S. A High-Spatial-Resolution Dataset of Human Thermal Stress Indices over South and East Asia. *Sci. Data* **2021**, *8*, 229. [CrossRef]
5. Lin, Y.; Huang, T.; Yang, W.; Hu, X.; Li, C. A Review on the Impact of Outdoor Environment on Indoor Thermal Environment. *Buildings* **2023**, *13*, 2600. [CrossRef]
6. Wei, R.; Yan, J.; Cui, Y.; Song, D.; Yin, X.; Sun, N. Studies on the Specificity of Outdoor Thermal Comfort during the Warm Season in High-Density Urban Areas. *Buildings* **2023**, *13*, 2473. [CrossRef]
7. Norouzi, M.; Chau, H.-W.; Jamei, E. Design and Site-Related Factors Impacting the Cooling Performance of Urban Parks in Different Climate Zones: A Systematic Review. *Land* **2024**, *13*, 2175. [CrossRef]
8. Qureshi, A.M.; Rachid, A.; Bartlett, D. Quantifying the Cooling Effect of Urban Heat Stress Interventions. *Int. J. Glob. Warm.* **2023**, *30*, 60. [CrossRef]
9. Requena-Ruiz, I.; Siret, D.; Stavropulos-Laffaille, X.; Leduc, T. Designing Thermally Sensitive Public Spaces: An Analysis through Urban Design Media. *J. Urban Des.* **2023**, *28*, 44–65. [CrossRef]
10. Cui, L.; Shibata, S. Exploring Climate-Adaptive Green-Space Designs for Hot and Humid Climates: Lessons from Japanese Dry Gardens. *Urban For. Urban Green.* **2024**, *93*, 128207. [CrossRef]
11. Kaveh, S.; Habibi, A.; Nikkar, M.; Aflaki, A. Optimizing Green Infrastructure Strategies for Microclimate Regulation and Air Quality Improvement in Urban Environments: A Case Study. *Nat.-Based Solut.* **2024**, *6*, 100167. [CrossRef]
12. Founda, D. Urban Thermal Risk. *Atmosphere* **2021**, *12*, 466. [CrossRef]
13. Bera, M.; Nag, P.K. Bioclimatic Design of Low-Cost Rural Dwellings. *Front. Built Environ.* **2022**, *8*, 773108. [CrossRef]
14. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 Statement: An Updated Guideline for Reporting Systematic Reviews. *BMJ* **2021**, *372*, n71. [CrossRef]
15. Aria, M.; Cuccurullo, C. Bibliometrix: An R-Tool for Comprehensive Science Mapping Analysis. *J. Informetr.* **2017**, *11*, 959–975. [CrossRef]
16. Hpoughten, F.C. Determining Equal Comfortlines. *J. Am. Soc. Heat Vent. Eng.* **1923**, *29*, 165–176.

17. Vernon, H.M.; Warner, C.G. The Influence of the Humidity of the Air on Capacity for Work at High Temperatures. *J. Hyg.* **1932**, *32*, 431–462. [CrossRef]
18. Yaglou, C.P.; Minard, D. Control of Heat Casualties at Military Training Centers. *AMA Arch. Ind. Health* **1957**, *16*, 302–316.
19. Thom, E.C. The Discomfort Index. *Weatherwise* **1959**, *12*, 57–60. [CrossRef]
20. Siple, P. Measurement of Dry Atmospheric Cooling in Subfreezing Temperatures. *Proc. Am. Philos. Soc.* **1945**, *89*, 177–199. [CrossRef]
21. Tew, M.; Battel, G.; Nelson, C.; AMS. AMS Implementation of a New Wind Chill Temperature Index by the National Weather Service. In Proceedings of the International Conference on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology, Orlando, FL, USA, 13–17 January 2002; pp. 203–205.
22. Gagge, A.P.; Burton, A.C.; Bazett, H.C. A Practical System of Units for the Description of the Heat Exchange of Man with His Environment. *Science* **1941**, *94*, 428–430. [CrossRef]
23. Fanger, P.O. *Thermal Comfort: Analysis and Applications in Environment Engeering*; Danish Technical Press: Copenhagen, Denmark, 1970.
24. *ISO 7730:2005*; Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria. International Organization for Standardization: Geneva, Switzerland, 2005.
25. *ANSI/ASHRAE Standard 55-2013*; Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers: Atlanta, GA, USA, 2013.
26. Ole Fanger, P.; Toftum, J. Extension of the PMV Model to Non-Air-Conditioned Buildings in Warm Climates. *Energy Build.* **2002**, *34*, 533–536. [CrossRef]
27. Gagge, A.P.; Stolwijk, J.A.J.; Nishi, Y. An Effective Temperature Scale Based on a Simple Model of Human Physiological Regulatory Response. *ASHRAE Trans.* **1971**, *77*, 21–36.
28. Gonzalez, R.; Nishi, Y.; Gagge, A.P. Experimental Evaluation of Standard Effective Temperature a New Biometeorological Index of Man's Thermal Discomfort. *Int. J. Biometeorol.* **1974**, *18*, 1–15. [CrossRef]
29. Katavoutas, G.; Flocas, H.A.; Matzarakis, A. Dynamic Modeling of Human Thermal Comfort after the Transition from an Indoor to an Outdoor Hot Environment. *Int. J. Biometeorol.* **2015**, *59*, 205–216. [CrossRef]
30. Krüger, E.; Rossi, F.; Drach, P. Calibration of the Physiological Equivalent Temperature Index for Three Different Climatic Regions. *Int. J. Biometeorol.* **2017**, *61*, 1323–1336. [CrossRef]
31. Höppe, P. The Physiological Equivalent Temperature—A Universal Index for the Biometeorological Assessment of the Thermal Environment. *Int. J. Biometeorol.* **1999**, *43*, 71–75. [CrossRef]
32. Lee, J.M. Understanding Volume and Correlations of Automated Walk Count: Predictors for Necessary, Optional, and Social Activities in Dilworth Park. *Environ. Plan. B-Urban Anal. City Sci.* **2021**, *48*, 331–347. [CrossRef]
33. Tanabe, S.; Kobayashi, K.; Nakano, J.; Ozeki, Y.; Konishi, M. Evaluation of Thermal Comfort Using Combined Multi-Node Thermoregulation (65MN) and Radiation Models and Computational Fluid Dynamics (CFD). *Energy Build.* **2002**, *34*, 637–646. [CrossRef]
34. Fiala, D.; Lomas, K.J.; Stohrer, M. Computer Prediction of Human Thermoregulatory and Temperature Responses to a Wide Range of Environmental Conditions. *Int. J. Biometeorol.* **2001**, *45*, 143–159. [CrossRef]
35. Huizenga, C.; Hui, Z.; Arens, E. A Model of Human Physiology and Comfort for Assessing Complex Thermal Environments. *Build. Environ.* **2001**, *36*, 691–699. [CrossRef]
36. Havenith, G.; Fiala, D.; Błazejczyk, K.; Richards, M.; Bröde, P.; Holmér, I.; Rintamaki, H.; Benshabat, Y.; Jendritzky, G. The UTCI-Clothing Model. *Int. J. Biometeorol.* **2012**, *56*, 461–470. [CrossRef] [PubMed]
37. Bröde, P.; Fiala, D.; Błażejczyk, K.; Holmér, I.; Jendritzky, G.; Kampmann, B.; Tinz, B.; Havenith, G. Deriving the Operational Procedure for the Universal Thermal Climate Index (UTCI). *Int. J. Biometeorol.* **2012**, *56*, 481–494. [CrossRef] [PubMed]
38. Blazejczyk, K.; Epstein, Y.; Jendritzky, G.; Staiger, H.; Tinz, B. Comparison of UTCI to Selected Thermal Indices. *Int. J. Biometeorol.* **2012**, *56*, 515–535. [CrossRef]
39. Potchter, O.; Cohen, P.; Lin, T.-P.; Matzarakis, A. Outdoor Human Thermal Perception in Various Climates: A Comprehensive Review of Approaches, Methods and Quantification. *Sci. Total Environ.* **2018**, *631*, 390–406. [CrossRef]
40. Dafri, I.; Alkama, D. Evaluation of Thermal Comfort in Outdoor Public Space: Case of Study: City of Annaba –Algeria-. *J. Phys. Conf. Ser.* **2019**, *1343*, 012026. [CrossRef]
41. Zhao, L.; Zhou, X.; Li, L.; He, S.; Chen, R. Study on Outdoor Thermal Comfort on a Campus in a Subtropical Urban Area in Summer. *Sustain. Cities Soc.* **2016**, *22*, 164–170. [CrossRef]
42. Fang, Z.; Feng, X.; Xu, X.; Zhou, X.; Lin, Z.; Ji, Y. Investigation into Outdoor Thermal Comfort Conditions by Different Seasonal Field Surveys in China, Guangzhou. *Int. J. Biometeorol.* **2019**, *63*, 1357–1368. [CrossRef]
43. Sharifi, E.; Boland, J. Passive Activity Observation (PAO) Method to Estimate Outdoor Thermal Adaptation in Public Space: Case Studies in Australian Cities. *Int. J. Biometeorol.* **2020**, *64*, 231–242. [CrossRef]

44. Faustini, F.B.; De Faria, J.R.G.; Fontes, M.S.G.D.C. The Influence of Thermal Comfort Conditions on User's Exposure Time in Open Spaces. *Int. J. Biometeorol.* **2020**, *64*, 243–252. [CrossRef]
45. Lam, C.K.C.; Hang, J. Solar Radiation Intensity and Outdoor Thermal Comfort in Royal Botanic Garden Melbourne during Heatwave Conditions. *Procedia Eng.* **2017**, *205*, 3456–3462. [CrossRef]
46. Nasir, R.A.; Ahmad, S.S.; Ahmed, A.Z. Perceived and Measured Adaptive Thermal Comfort at an Outdoor Shaded Recreational Area in Malaysia. *Adv. Mater. Res.* **2013**, *610*, 1083–1086. [CrossRef]
47. Zhen, M.; Zou, W.; Zheng, R.; Lu, Y. Urban Outdoor Thermal Environment and Adaptive Thermal Comfort during the Summer. *Env. Sci. Pollut. Res.* **2022**, *29*, 77864–77883. [CrossRef] [PubMed]
48. Huang, H.; Peng, M. The Outdoor Thermal Comfort of Urban Square: A Field Study in a Cold Season in Chongqing. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *467*, 012215. [CrossRef]
49. Huang, T.; Niu, J.; Mak, C.M.; Lin, Z. Comparisons of Respondent Thermal Perceptions in Underneath-Elevated-Building (UEB) Areas and Direct-Radiated (DR) Areas. *Procedia Eng.* **2017**, *205*, 4165–4171. [CrossRef]
50. Hartabela, D.; Dewancker, B.J.; Koerniawan, M.D. A Relationship Between Micro-Meteorological and Personal Variables of Outdoor Thermal Comfort: A Case Study in Kitakyushu, Japan. *Sustainability* **2021**, *13*, 13634. [CrossRef]
51. Lau, K.K.-L.; Choi, C.Y. The Influence of Perceived Aesthetic and Acoustic Quality on Outdoor Thermal Comfort in Urban Environment. *Build. Environ.* **2021**, *206*, 108333. [CrossRef]
52. Hao, T.; Chang, H.; Liang, S.; Jones, P.; Chan, P.W.; Li, L.; Huang, J. Heat and Park Attendance: Evidence from "Small Data" and "Big Data" in Hong Kong. *Build. Environ.* **2023**, *234*, 110123. [CrossRef]
53. Jaung, W.; Carrasco, L.R. Using Mobile Phone Data to Examine Weather Impacts on Recreational Ecosystem Services in an Urban Protected Area. *Sci. Rep.* **2021**, *11*, 5544. [CrossRef]
54. Elraouf, R.A.; ELMokadem, A.; Megahed, N.; Eleinen, O.A.; Eltarabily, S. Evaluating Urban Outdoor Thermal Comfort: A Validation of ENVI-Met Simulation through Field Measurement. *J. Build. Perform. Simul.* **2022**, *15*, 268–286. [CrossRef]
55. Park, S.; Tuller, S.E.; Jo, M. Application of Universal Thermal Climate Index (UTCI) for Microclimatic Analysis in Urban Thermal Environments. *Landsc. Urban Plan.* **2014**, *125*, 146–155. [CrossRef]
56. Sayad, B.; Alkama, D.; Ahmad, H.; Baili, J.; Aljahdaly, N.H.; Menni, Y. Nature-Based Solutions to Improve the Summer Thermal Comfort Outdoors. *Case Stud. Therm. Eng.* **2021**, *28*, 101399. [CrossRef]
57. Yang, W.; Wong, N.H.; Li, C.-Q. Effect of Street Design on Outdoor Thermal Comfort in an Urban Street in Singapore. *J. Urban Plann. Dev.* **2016**, *142*, 05015003. [CrossRef]
58. Nie, T.; Lai, D.; Liu, K.; Lian, Z.; Yuan, Y.; Sun, L. Discussion on Inapplicability of Universal Thermal Climate Index (UTCI) for Outdoor Thermal Comfort in Cold Region. *Urban Clim.* **2022**, *46*, 101304. [CrossRef]
59. Pigliautile, I.; Chàfer, M.; Pisello, A.L.; Pérez, G.; Cabeza, L.F. Inter-Building Assessment of Urban Heat Island Mitigation Strategies: Field Tests and Numerical Modelling in a Simplified-Geometry Experimental Set-Up. *Renew. Energy* **2020**, *147*, 1663–1675. [CrossRef]
60. Krüger, E.L.; Costa, T. Interferences of Urban Form on Human Thermal Perception. *Sci. Total Environ.* **2019**, *653*, 1067–1076. [CrossRef]
61. De Masi, R.F.; Ruggiero, S.; Vanol, G.P. Acrylic White Paint of Industrial Sector for Cool Roofing Application: Experimental Investigation of Summer Behavior and Aging Problem Under Mediterranean Climate. *Sol. Energy* **2018**, *169*, 468–487. [CrossRef]
62. Rosso, F.; Fabiani, C.; Chiatti, C.; Pisello, A.L. Cool, Photoluminescent Paints towards Energy Consumption Reductions in the Built Environment. *J. Phys. Conf. Ser.* **2019**, *1343*, 012198. [CrossRef]
63. Han, B.; Zhang, K.; Yu, X. Enhance the Thermal Storage of Cement-Based Composites with Phase Change Materials and Carbon Nanotubes. *J. Sol. Energy Eng.-Trans. ASME* **2013**, *135*, 024505. [CrossRef]
64. Dong, S.; Quek, J.Y.; Van Herk, A.M.; Jana, S. Polymer-Encapsulated TiO_2 for the Improvement of NIR Reflectance and Total Solar Reflectance of Cool Coatings. *Ind. Eng. Chem. Res.* **2020**, *59*, 17901–17910. [CrossRef]
65. Naboni, E.; Silvia, C.; Meloni, M.; Scartezzini, J.-L. Outdoor Comfort Simulation of Complex Architectural Designs: A Review of Simulation Tools from the Designer Perspective. In Proceedings of the 2018 Building Performance Analysis Conference and SimBuild Co-Organized by ASHRAE and IBPSA, Chicago, IL, USA, 26–28 September 2018; pp. 659–666.
66. Coccolo, S.; Mauree, D.; Naboni, E.; Kaempf, J.; Scartezzini, J.-L. On the Impact of the Wind Speed on the Outdoor Human Comfort: A Sensitivity Analysis. *Energy Procedia* **2017**, *122*, 481–486. [CrossRef]
67. Liu, S.; Zhao, J.; Xu, M.; Ahmadian, E. Effects of Landscape Patterns on the Summer Microclimate and Human Comfort in Urban Squares in China. *Sustain. Cities Soc.* **2021**, *73*, 103099. [CrossRef]
68. Naboni, E.; Meloni, M.; Coccolo, S.; Kaempf, J.; Scartezzini, J.-L. An Overview of Simulation Tools for Predicting the Mean Radiant Temperature in an Outdoor Space. *Energy Procedia* **2017**, *122*, 1112–1117. [CrossRef]
69. Chen, G.; Rong, L.; Zhang, G. Unsteady-State CFD Simulations on the Impacts of Urban Geometry on Outdoor Thermal Comfort within Idealized Building Arrays. *Sustain. Cities Soc.* **2021**, *74*, 103187. [CrossRef]

70. Chen, Y.-C.; Lin, T.-P.; Matzarakis, A. Comparison of Mean Radiant Temperature from Field Experiment and Modelling: A Case Study in Freiburg, Germany. *Theor. Appl. Climatol.* **2014**, *118*, 535–551. [CrossRef]
71. Jaenicke, B.; Meier, F.; Hoelscher, M.-T.; Scherer, D. Evaluating the Effects of Facade Greening on Human Bioclimate in a Complex Urban Environment. *Adv. Meteorol.* **2015**, *2015*, 747259. [CrossRef]
72. Gal, C.V.; Kantor, N. Modeling Mean Radiant Temperature in Outdoor Spaces, A Comparative Numerical Simulation and Validation Study. *Urban Clim.* **2020**, *32*, 100571. [CrossRef]
73. Lau, K.K.-L.; Lindberg, F.; Rayner, D.; Thorsson, S. The Effect of Urban Geometry on Mean Radiant Temperature under Future Climate Change: A Study of Three European Cities. *Int. J. Biometeorol.* **2015**, *59*, 799–814. [CrossRef]
74. Thom, J.K.; Coutts, A.M.; Broadbent, A.M.; Tapper, N.J. The Influence of Increasing Tree Cover on Mean Radiant Temperature across a Mixed Development Suburb in Adelaide, Australia. *Urban For. Urban Green.* **2016**, *20*, 233–242. [CrossRef]
75. Konarska, J.; Lindberg, F.; Larsson, A.; Thorsson, S.; Holmer, B. Transmissivity of Solar Radiation through Crowns of Single Urban Trees-Application for Outdoor Thermal Comfort Modelling. *Theor. Appl. Climatol.* **2014**, *117*, 363–376. [CrossRef]
76. Shashua-Bar, L.; Hoffman, M. Geometry and Orientation Aspects in Passive Cooling of Canyon Streets with Trees. *Energy Build.* **2003**, *35*, 61–68. [CrossRef]
77. Jaenicke, B.; Milosevic, D.; Manavvi, S. Review of User-Friendly Models to Improve the Urban Micro-Climate. *Atmosphere* **2021**, *12*, 1291. [CrossRef]
78. Lai, D.; Liu, W.; Gan, T.; Liu, K.; Chen, Q. A Review of Mitigating Strategies to Improve the Thermal Environment and Thermal Comfort in Urban Outdoor Spaces. *Sci. Total Environ.* **2019**, *661*, 337–353. [CrossRef] [PubMed]
79. Blocken, B. LES over RANS in Building Simulation for Outdoor and Indoor Applications: A Foregone Conclusion? *Build. Simul.* **2018**, *11*, 821–870. [CrossRef]
80. Ghani, S.; Bialy, E.M.; Bakochristou, F.; Gamaledin, S.M.A.; Rashwan, M.M.; Hughes, B. Thermal Comfort Investigation of an Outdoor Air-Conditioned Area in a Hot and Arid Environment. *Sci. Technol. Built Environ.* **2017**, *23*, 1113–1131. [CrossRef]
81. Li, Z.; Zhang, H.; Wen, C.-Y.; Yang, A.-S.; Juan, Y.-H. Effects of Height-Asymmetric Street Canyon Configurations on Outdoor Air Temperature and Air Quality. *Build. Environ.* **2020**, *183*, 107195. [CrossRef]
82. Shen, X.; Li, J.; Wang, S.; Su, L.; Li, L. The Impact of Tree-Planting Location on the Microclimate and Thermal Comfort of the Micro-Public Space. *Pol. J. Environ. Stud.* **2023**, *32*, 717–730. [CrossRef]
83. Li, J.; Liu, J.; Srebric, J.; Hu, Y.; Liu, M.; Su, L.; Wang, S. The Effect of Tree-Planting Patterns on the Microclimate within a Courtyard. *Sustainability* **2019**, *11*, 1665. [CrossRef]
84. Xiao, J.; Yuizono, T. Climate-Adaptive Landscape Design: Microclimate and Thermal Comfort Regulation of Station Square in the Hokuriku Region, Japan. *Build. Environ.* **2022**, *212*, 108813. [CrossRef]
85. Evola, G.; Costanzo, V.; Magri, C.; Margani, G.; Marletta, L.; Naboni, E. A Novel Comprehensive Workflow for Modelling Outdoor Thermal Comfort and Energy Demand in Urban Canyons: Results and Critical Issues. *Energy Build.* **2020**, *216*, 109946. [CrossRef]
86. Ibrahim, Y.; Kershaw, T.; Shepherd, P.; Elwy, I. A Parametric Optimisation Study of Urban Geometry Design to Assess Outdoor Thermal Comfort. *Sustain. Cities Soc.* **2021**, *75*, 103352. [CrossRef]
87. Aghamolaei, R.; Azizi, M.M.; Aminzadeh, B.; Mirzaei, P.A. A Tempo-Spatial Modelling Framework to Assess Outdoor Thermal Comfort of Complex Urban Neighbourhoods. *Urban Clim.* **2020**, *33*, 100665. [CrossRef]
88. Khraiwesh, M.M.; Genovese, P.V. Outdoor Thermal Comfort Integrated with Energy Consumption for Urban Block Design Optimization: A Study of the Hot-Summer Mediterranean City of Irbid, Jordan. *Sustainability* **2023**, *15*, 8412. [CrossRef]
89. Milošević, D.D.; Bajšanski, I.V.; Savić, S.M. Influence of Changing Trees Locations on Thermal Comfort on Street Parking Lot and Footways. *Urban For. Urban Green.* **2017**, *23*, 113–124. [CrossRef]
90. Zhang, T.; Hu, Q.; Ding, Q.; Zhou, D.; Gao, W.; Fukuda, H. Towards a Rural Revitalization Strategy for the Courtyard Layout of Vernacular Dwellings Based on Regional Adaptability and Outdoor Thermal Performance in the Gully Regions of the Loess Plateau, China. *Sustainability* **2021**, *13*, 13074. [CrossRef]
91. López-Cabeza, V.P.; Diz-Mellado, E.; Rivera-Gómez, C.; Galán-Marín, C.; Samuelson, H.W. Thermal Comfort Modelling and Empirical Validation of Predicted Air Temperature in Hot-Summer Mediterranean Courtyards. *J. Build. Perform. Simul.* **2022**, *15*, 39–61. [CrossRef]
92. Tabadkani, A.; Aghasizadeh, S.; Banihashemi, S.; Hajirasouli, A. Courtyard Design Impact on Indoor Thermal Comfort and Utility Costs for Residential Households: Comparative Analysis and Deep-Learning Predictive Model. *Front. Archit. Res.* **2022**, *11*, 963–980. [CrossRef]
93. Liu, Z.; Jin, Y.; Jin, H. The Effects of Different Space Forms in Residential Areas on Outdoor Thermal Comfort in Severe Cold Regions of China. *Int. J. Environ. Res. Public Health* **2019**, *16*, 3960. [CrossRef]
94. Hado, A.K.; Hassan, S.A. Iraq Green Buildings Code Effect on Improving Outdoor Thermal Comfort for Residential Complex. *Asian J. Water Environ. Pollut.* **2023**, *20*, 115–120. [CrossRef]
95. Fahmy, M.; Sharples, S.; Yahiya, M. LAI Based Trees Selection for Mid Latitude Urban Developments: A Microclimatic Study in Cairo, Egypt. *Build. Environ.* **2010**, *45*, 345–357. [CrossRef]

96. Karimi, A.; Bayat, A.; Mohammadzadeh, N.; Mohajerani, M.; Yeganeh, M. Microclimatic Analysis of Outdoor Thermal Comfort of High-Rise Buildings with Different Configurations in Tehran: Insights from Field Surveys and Thermal Comfort Indices. *Build. Environ.* **2023**, *240*, 110445. [CrossRef]
97. Zafarmandi, S.; Mahdavinejad, M.; Norford, L.; Matzarakis, A. Analyzing Thermal Comfort Sensations in Semi-Outdoor Space on a University Campus: On-Site Measurements in Tehran's Hot and Cold Seasons. *Atmosphere* **2022**, *13*, 1034. [CrossRef]
98. Zhang, L.; Zhan, Q.; Lan, Y. Effects of the Tree Distribution and Species on Outdoor Environment Conditions in a Hot Summer and Cold Winter Zone: A Case Study in Wuhan Residential Quarters. *Build. Environ.* **2018**, *130*, 27–39. [CrossRef]
99. López-Cabeza, V.P.; Diz-Mellado, E.; Rivera-Gómez, C.A.; Galán-Marín, C. Shade and Thermal Comfort in Courtyards: Experimental versus Simulation Results. *Buildings* **2022**, *12*, 1961. [CrossRef]
100. Mutani, G.; Todeschi, V.; Beltramino, S. Improving Outdoor Thermal Comfort in Built Environment Assessing the Impact of Urban Form and Vegetation. *Int. J. Heat Technol.* **2022**, *40*, 23–31. [CrossRef]
101. Li, K.; Zhang, Y.; Zhao, L. Outdoor Thermal Comfort and Activities in the Urban Residential Community in a Humid Subtropical Area of China. *Energy Build.* **2016**, *133*, 498–511. [CrossRef]
102. Yang, J.; Zhao, Y.; Zou, Y.; Xia, D.; Lou, S.; Guo, T.; Zhong, Z. Improving the Thermal Comfort of an Open Space via Landscape Design: A Case Study in Hot and Humid Areas. *Atmosphere* **2022**, *13*, 1604. [CrossRef]
103. Yang, J.; Zhao, Y.; Guo, T.; Luo, X.; Ji, K.; Zhou, M.; Wan, F. The Impact of Tree Species and Planting Location on Outdoor Thermal Comfort of a Semi-Outdoor Space. *Int. J. Biometeorol.* **2023**, *67*, 1689–1701. [CrossRef]
104. Shata, R.O.; Mahmoud, A.H.; Fahmy, M. Correlating the Sky View Factor with the Pedestrian Thermal Environment in a Hot Arid University Campus Plaza. *Sustainability* **2021**, *13*, 468. [CrossRef]
105. Nasrollahi, N.; Hatami, M.; Khastar, S.R.; Taleghani, M. Numerical Evaluation of Thermal Comfort in Traditional Courtyards to Develop New Microclimate Design in a Hot and Dry Climate. *Sustain. Cities Soc.* **2017**, *35*, 449–467. [CrossRef]
106. Feitosa, R.C.; Wilkinson, S.J.; Oliveira, B.; Hacon, S. Wind and Greenery Effects in Attenuating Heat Stress: A Case Study. *J. Clean. Prod.* **2021**, *291*, 125919. [CrossRef]
107. Chen, X.; Gao, L.; Xue, P.; Du, J.; Liu, J. Investigation of Outdoor Thermal Sensation and Comfort Evaluation Methods in Severe Cold Area. *Sci. Total Environ.* **2020**, *749*, 141520. [CrossRef] [PubMed]
108. Kenawy, I.; Elkadi, H. The Outdoor Thermal Benchmarks in Melbourne Urban Climate. *Sustain. Cities Soc.* **2018**, *43*, 587–600. [CrossRef]
109. Yang, W.; Wong, N.H.; Lin, Y. Thermal Comfort in High-Rise Urban Environments in Singapore. *Procedia Eng.* **2015**, *121*, 2125–2131. [CrossRef]
110. Xiong, K.; He, B.-J. Wintertime Outdoor Thermal Sensations and Comfort in Cold-Humid Environments of Chongqing China. *Sustain. Cities Soc.* **2022**, *87*, 104203. [CrossRef]
111. Khalili, S.; Fayaz, R.; Zolfaghari, S.A. Analyzing Outdoor Thermal Comfort Conditions in a University Campus in Hot-Arid Climate: A Case Study in Birjand, Iran. *Urban Clim.* **2022**, *43*, 101128. [CrossRef]
112. Altunkasa, C.; Uslu, C. Use of Outdoor Microclimate Simulation Maps for a Planting Design to Improve Thermal Comfort. *Sustain. Cities Soc.* **2020**, *57*, 102137. [CrossRef]
113. Fabbri, K.; Ugolini, A.; Iacovella, A.; Bianchi, A.P. The Effect of Vegetation in Outdoor Thermal Comfort in Archaeological Area in Urban Context. *Build. Environ.* **2020**, *175*, 106816. [CrossRef]
114. Xue, S.; Xiao, Y. Study on the Outdoor Thermal Comfort Threshold of Lingnan Garden in Summer. *Procedia Eng.* **2016**, *169*, 422–430. [CrossRef]
115. Ma, X.; Wang, M.; Zhao, J.; Zhang, L.; Liu, W. Performance of Different Urban Design Parameters in Improving Outdoor Thermal Comfort and Health in a Pedestrianized Zone. *Int. J. Environ. Res. Public Health* **2020**, *17*, 2258. [CrossRef]
116. Losi, G.; Bonzanini, A.; Aquino, A.; Poesio, P. Analysis of Thermal Comfort in a Football Stadium Designed for Hot and Humid Climates by CFD. *J. Build. Eng.* **2021**, *33*, 101599. [CrossRef]
117. Lin, C.-H.; Lin, T.-P.; Hwang, R.-L. Thermal Comfort for Urban Parks in Subtropics: Understanding Visitor's Perceptions, Behavior and Attendance. *Adv. Meteorol.* **2013**, *2013*, 640473. [CrossRef]
118. Zhou, Z.; Chen, H.; Deng, Q.; Mochida, A. A Field Study of Thermal Comfort in Outdoor and Semi-Outdoor Environments in a Humid Subtropical Climate City. *J. Asian Archit. Build. Eng.* **2013**, *12*, 73–79. [CrossRef]
119. Zhou, Z.; Deng, Q.; Yang, W.; Zhou, J. Effect of Seasonal Adaptation on Outdoor Thermal Comfort in a Hot-Summer and Cold-Winter City. *Adv. Build. Energy Res.* **2020**, *14*, 202–217. [CrossRef]
120. Lin, T.-P.; de Dear, R.; Hwang, R.-L. Effect of Thermal Adaptation on Seasonal Outdoor Thermal Comfort. *Int. J. Climatol.* **2011**, *31*, 302–312. [CrossRef]
121. Tsitoura, M.; Tsoutsos, T.; Daras, T. Evaluation of Comfort Conditions in Urban Open Spaces. Application in the Island of Crete. *Energy Convers. Manag.* **2014**, *86*, 250–258. [CrossRef]
122. Abdallah, A.S.H.; Al-Saadi, S.N.J. Outdoor Space Quality: Impact of Deep Canyon Thermal Comfort in an Urban Residential Community. *Sci. Technol. Built Environ.* **2020**, *27*, 477–488. [CrossRef]

123. Al-Atrash, F.Z.; Al-Ayyoub, A. Evaluating Urban Outdoor Thermal Comfort in Jabal Al Natheef Amman. *Sustainability* **2023**, *15*, 4092. [CrossRef]
124. Guo, F.; Wang, Z.; Dong, J.; Zhang, H.; Lu, X.; Lau, S.S.; Miao, Y. Spatial Differences in Outdoor Thermal Comfort during the Transition Season in Cold Regions of China. *Buildings* **2022**, *12*, 720. [CrossRef]
125. Lam, C.K.C.; Lau, K.K.-L. Effect of Long-Term Acclimatization on Summer Thermal Comfort in Outdoor Spaces: A Comparative Study between Melbourne and Hong Kong. *Int. J. Biometeorol.* **2018**, *62*, 1311–1324. [CrossRef]
126. Kumar, P.; Sharma, A. Assessing the Outdoor Thermal Comfort Conditions of Exercising People in the Semi-Arid Region of India. *Sustain. Cities Soc.* **2022**, *76*, 103366. [CrossRef]
127. Chow, W.T.L.; Akbar, S.N.A.B.A.; Heng, S.L.; Roth, M. Assessment of Measured and Perceived Microclimates within a Tropical Urban Forest. *Urban For. Urban Green.* **2016**, *16*, 62–75. [CrossRef]
128. Yuan, J.; Farnham, C.; Emura, K. Effect of Different Reflection Directional Characteristics of Building Facades on Outdoor Thermal Environment and Indoor Heat Loads by CFD Analysis. *Urban Clim.* **2021**, *38*, 100875. [CrossRef]
129. Oh, W.; Ooka, R.; Nakano, J.; Kikumoto, H.; Ogawa, O. Environmental Index for Evaluating Thermal Sensations in a Mist Spraying Environment. *Build. Environ.* **2019**, *161*, 106219. [CrossRef]
130. Mahgoub, A.O.; Gowid, S.; Ghani, S. Global Evaluation of WBGT and SET Indices for Outdoor Environments Using Thermal Imaging and Artificial Neural Networks. *Sustain. Cities Soc.* **2020**, *60*, 102182. [CrossRef]
131. Abdel-Ghany, A.M.; Al-Helal, I.M.; Shady, M.R. Human Thermal Comfort and Heat Stress in an Outdoor Urban Arid Environment: A Case Study. *Adv. Meteorol.* **2013**, *2013*, 693541. [CrossRef]
132. Fang, Z.; Feng, X.; Liu, J.; Lin, Z.; Mak, C.M.; Niu, J.; Tse, K.-T.; Xu, X. Investigation into the Differences among Several Outdoor Thermal Comfort Indices against Field Survey in Subtropics. *Sustain. Cities Soc.* **2019**, *44*, 676–690. [CrossRef]
133. Morakinyo, T.E.; Dahanayake, K.W.D.; Kalani, C.; Adegun, O.B.; Balogun, A.A. Modelling the Effect of Tree-Shading on Summer Indoor and Outdoor Thermal Condition of Two Similar Buildings in a Nigerian University. *Energy Build.* **2016**, *130*, 721–732. [CrossRef]
134. Zhu, S.; Chen, M.; Lu, S.; Mai, X. Influence of Urban Geometry on Thermal Environment of Urban Street Canyons in Hong Kong. *Buildings* **2022**, *12*, 1836. [CrossRef]
135. Sahoh, B.; Kaewrat, C.; Yeranee, K.; Kittiphattanabawon, N.; Kliangkhlao, M. Causal AI-Powered Event Interpretation: A Cause-and-Effect Discovery for Indoor Thermal Comfort Measurements. *IEEE Internet Things J.* **2022**, *9*, 23188–23200. [CrossRef]
136. Xi, T.; Wang, M.; Cao, E.; Li, J.; Wang, Y.; Sa'ad, S.U. Preliminary Research on Outdoor Thermal Comfort Evaluation in Severe Cold Regions by Machine Learning. *Buildings* **2024**, *14*, 284. [CrossRef]
137. Eslamirad, N.; Malekpour Kolbadinejad, S.; Mahdavinejad, M.; Mehranrad, M. Thermal Comfort Prediction by Applying Supervised Machine Learning in Green Sidewalks of Tehran. *Smart Sustain. Built Environ.* **2020**, *9*, 361–374. [CrossRef]
138. Jeong, J.; Jeong, J.; Lee, M.; Lee, J.; Chang, S. Data-Driven Approach to Develop Prediction Model for Outdoor Thermal Comfort Using Optimized Tree-Type Algorithms. *Build. Environ.* **2022**, *226*, 109663. [CrossRef]
139. Prasad, P.S.H.; Satyanarayana, A.N.V. Assessment of Outdoor Thermal Comfort Using Landsat 8 Imageries with Machine Learning Tools over a Metropolitan City of India. *Pure Appl. Geophys.* **2023**, *180*, 3621–3637. [CrossRef]
140. Ngarambe, J.; Yun, G.Y.; Santamouris, M. The Use of Artificial Intelligence (AI) Methods in the Prediction of Thermal Comfort in Buildings: Energy Implications of AI-Based Thermal Comfort Controls. *Energy Build.* **2020**, *211*, 109807. [CrossRef]
141. Shahrestani, S.S.; Zomorodian, Z.S.; Karami, M.; Mostafavi, F. A Novel Machine Learning-Based Framework for Mapping Outdoor Thermal Comfort. *Adv. Build. Energy Res.* **2023**, *17*, 53–72. [CrossRef]
142. Shah, R.; Pandit, R.; Gaur, M. Determining the Influence of Meteorological Parameters on Outdoor Thermal Comfort Using ANFIS and ANN. *Mausam* **2023**, *74*, 741–760. [CrossRef]
143. Matallah, M.E.; Mahar, W.A.; Bughio, M.; Alkama, D.; Ahriz, A.; Bouzaher, S. Prediction of Climate Change Effect on Outdoor Thermal Comfort in Arid Region. *Energies* **2021**, *14*, 4730. [CrossRef]
144. Zhang, J.; Zhang, F.; Gou, Z.; Liu, J. Assessment of Macroclimate and Microclimate Effects on Outdoor Thermal Comfort via Artificial Neural Network Models. *Urban Clim.* **2022**, *42*, 101134. [CrossRef]
145. Ghahramani, A.; Galicia, P.; Lehrer, D.; Varghese, Z.; Wang, Z.; Pandit, Y. Artificial Intelligence for Efficient Thermal Comfort Systems: Requirements, Current Applications and Future Directions. *Front. Built Environ.* **2020**, *6*, 49. [CrossRef]
146. Zhao, Y.; Genovese, P.V.; Li, Z. Intelligent Thermal Comfort Controlling System for Buildings Based on IoT and AI. *Future Internet* **2020**, *12*, 30. [CrossRef]
147. Siqi, J.; Yuhong, W.; Nyuk Hien, W. The Effect of Urban Greening on Pedestrian's Thermal Comfort and Walking Behaviour. *E3S Web Conf.* **2023**, *396*, 05013. [CrossRef]
148. Lai, D.; Jia, S.; Qi, Y.; Liu, J. Window-Opening Behavior in Chinese Residential Buildings Across Different Climate Zones. *Build. Environ.* **2018**, *142*, 234–243. [CrossRef]
149. Guttikunda, S.K.; Nishadh, K.A.; Jawahar, P. Air Pollution Knowledge Assessments (APnA) for 20 Indian Cities. *Urban Clim.* **2019**, *27*, 124–141. [CrossRef]

150. Clark, C.; Busiek, B.; Adriaens, P. Quantifying Thermal Impacts of Green Infrastructure: Review and Gaps. *Proc. Water Environ. Fed.* **2010**, *2010*, 69–77. [CrossRef]
151. Xiao, J.; Yuizono, T.; Li, R. Synergistic Landscape Design Strategies to Renew Thermal Environment: A Case Study of a Cfa-Climate Urban Community in Central Komatsu City, Japan. *Sustainability* **2024**, *16*, 5582. [CrossRef]
152. Wai, C.Y.; Tariq, M.A.U.R.; Muttil, N. A Systematic Review on the Existing Research, Practices, and Prospects Regarding Urban Green Infrastructure for Thermal Comfort in a High-Density Urban Context. *Water* **2022**, *14*, 2496. [CrossRef]
153. Xu, H.; Liao, J.; Hong, Y. The Effect of Green Stormwater Infrastructures on Urban-Tier Human Thermal Comfort—A Case Study in High-Density Urban Blocks. *Forests* **2024**, *15*, 862. [CrossRef]
154. Lin, J.; Brown, R. Integrating Microclimate into Landscape Architecture for Outdoor Thermal Comfort: A Systematic Review. *Land* **2021**, *10*, 196. [CrossRef]
155. Kianmehr, A.; Lim, T.C. Quantifying Interactive Cooling Effects of Morphological Parameters and Vegetation-Related Landscape Features during an Extreme Heat Event. *Climate* **2022**, *10*, 60. [CrossRef]
156. Chen, W.; Liu, J.; Ning, X.; Du, L.; Zhang, Y.; Wu, C. Low-Carbon City Building and Green Development: New Evidence from Quasi Natural Experiments from 277 Cities in China. *Sustainability* **2023**, *15*, 11609. [CrossRef]
157. Naheed, S.; Shooshtarian, S. A Review of Cultural Background and Thermal Perceptions in Urban Environments. *Sustainability* **2021**, *13*, 9080. [CrossRef]
158. Wang, L.; Zhang, L.; Zhang, T.; Hu, Y.; He, J. The Impact Mechanism of Urban Built Environment on Urban Greenways Based on Computer Vision. *Forests* **2024**, *15*, 1171. [CrossRef]