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Review

A Comparative Analysis of Outdoor Thermal Comfort Indicators Applied in China and Other Countries

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Abstract: Outdoor thermal comfort is an important criterion for evaluating the quality of outdoor activity environments and is also a significant indicator for assessing sustainable building design. Over the past century, more than 165 indoor and outdoor thermal comfort indexes have been developed to define human thermal comfort conditions under various circumstances and to quantify indoor and outdoor thermal environmental conditions. However, in the process of outdoor thermal comfort indicators becoming widely used worldwide, it remains a pressing research issue to compare the current state of application in China and other countries, identify the key areas of application for both sides, and outline the trends in outdoor thermal comfort index application. This study analyzed 346 articles on outdoor thermal comfort indicators. Employing bibliometric methods, we outline the general landscape of outdoor thermal comfort index applications in China and other countries. Additionally, we utilize comparative analysis to uncover similarities and differences in the research focus on outdoor thermal comfort. The research findings indicate the following: (1) Compared to China, other countries started outdoor thermal comfort index application research earlier. Their papers have higher average citation counts and engage in close academic collaborations. However, the quantity of published papers is fewer than in China. (2) The top five frequently used indexes in both China and other countries are PET (including mPET), UTCI, PMV, SET* (including OUT_SET*), and THI (including DI). China tends to use PET and UTCI more frequently than other countries. (3) The potential future directions for outdoor thermal comfort index applications in both China and other countries include: “monitoring and controlling regional outdoor thermal comfort at the temporal and spatial scales”, “multi-factors coupling effects on outdoor thermal comfort”, “human health assessment and prediction based on outdoor thermal comfort”, and “utilizing computational algorithms to calculate outdoor thermal comfort”. This study can serve as a reference for researchers and designers in the industry, contributing to the creation of sustainable outdoor environments.

Keywords: bibliometrics; human thermal comfort indicators; outdoor thermal comfort; outdoor thermal perception; outdoor heat stress; outdoor thermal environment

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1. Introduction

By the end of 2022, the global urban population is expected to constitute 57% of the total population, which is attributed to socioeconomic advancements [1]. This urbanization surge has contributed to an increase in building density and urban area expansion. Consequently, the urban outdoor thermal environment is constantly deteriorating, seriously affecting the outdoor thermal comfort of residents [2]. Moreover, urban outdoor spaces constitute a crucial component of the urban living environment. Outdoor areas that offer favorable climates and high levels of participation not only contribute to the physical and mental well-being of individuals [3], but also effectively reduce the architectural energy consumption associated with the use of buildings [4], thereby supporting the development of sustainable cities. In particular, outdoor thermal comfort has become a crucial criterion for evaluating the quality of outdoor activity environments. Therefore, outdoor thermal comfort indicators, as crucial tools for quantifying human perception of outdoor thermal conditions, assist designers and decision-makers in accurately assessing the outdoor thermal environment and enhancing outdoor thermal comfort conditions.

As outdoor thermal comfort garners increasing attention from various sectors of society, there has been a growing body of literature reviews in the field of outdoor thermal comfort. However, there is a limited number of literature reviews focused on outdoor thermal comfort from a national or regional perspective. Among these, studies specifically examining outdoor thermal comfort from a national or regional standpoint tend to concentrate on singular aspects and rarely encompass a comprehensive overview of the research framework in outdoor thermal comfort. For example, Li et al. provided a review of commonly used outdoor thermal comfort indexes, outdoor thermal perception, and optimization strategies in China [5]; Aghamohammadi et al. summarized the assessment methods for outdoor thermal comfort in Southeast Asia [6]; and Binarti et al. evaluated the neutral range of outdoor thermal comfort in hot and humid regions [7], Furthermore, even when there is a comprehensive review of outdoor thermal comfort research, it tends to be confined to a single country, with little attention given to comparative analyses of research trends among different countries or regions. For instance, Shooshtarian et al. systematically reviewed the key focus, research methods, and research findings of outdoor thermal comfort research in Australia [8]. Therefore, for researchers in China, it is crucial that this paper, by synthesizing the outdoor thermal comfort research frameworks in both China and other countries and comparing the differences in their studies, can unveil the trends in the application of outdoor thermal comfort indexes.

In terms of research methodology, most outdoor thermal comfort-related reviews rely on the authors' research experience in the field to organize and analyze the literature. For example, Potchter et al. organized and analyzed the literature on biometeorological research strategies and methods from 2001 to 2021 in a tabular format [9]. Jim et al. compared relevant terms and calculation methods for outdoor thermal benchmarks in 24 studies on outdoor thermal comfort in a tabular format [10]. Potchter et al. summarized and compared the literature from 2001 to 2017 that included outdoor conditions and human thermal perception using charts [11]. Sharma et al. summarized and compared the literature related to outdoor thermal comfort from 2001 to 2019 using charts [12]. Unfortunately, bibliometrics, as a visualization method for understanding research trends and hotspots in specific academic fields [13,14], is seldom applied in the field of outdoor thermal comfort research. Its application is notably lacking in comparing outdoor thermal comfort research overviews, themes, and trends among different countries or regions. Therefore, the use of bibliometrics in this study helps provide a clearer understanding of the differences in research overviews, themes, and trends between China and other countries.

Therefore, this paper focuses on the application of outdoor thermal comfort indexes and establishes four main objectives through bibliometric research methods. Firstly, to compare the current research status of the application of outdoor thermal comfort indexes in China and other countries. Secondly, to summarize the similarities and differences in how the themes of outdoor thermal comfort indexes between China and other countries are applied. Thirdly, to generalize the research trends in the application of outdoor thermal comfort indexes in China and other countries. Fourthly, to discuss potential research areas of outdoor thermal comfort indexes from theoretical and practical perspectives. The summary of potential applications for these outdoor thermal comfort indicators can serve as a basis for designers to optimize outdoor thermal environments. This, in turn, facilitates the creation of sustainable outdoor environments conducive to human activities.

2. Research Methodology and Data Sources

2.1. Research Methodology

This study primarily employed three research methods: a literature review, bibliometric analysis, and comparative analysis. The research utilized a literature review to analyze the development, types, and research themes of outdoor thermal comfort indexes. Through bibliometric analysis, it quantified the current status and trends of outdoor thermal comfort index applications in China and other countries. Finally, by means of comparative analysis, it compared the similarities and differences in the current status and trends of the application of outdoor thermal comfort indexes between the two sides.

2.2. Data Source

The literature reviewed in this study was sourced from the core dataset of Web of Science [15]. The Science Citation Index Expanded (SCIE) is recognized as a premier bibliometric research database and the most respected academic journal system. It holds articles of rigorous peer-review quality [16]. Data were retrieved on 25 May 2023. To conduct a broad search of relevant articles on outdoor thermal comfort indicator applications, an advanced search in Web of Science was configured with the following terms: "((TS = (biological meteorological index*)) OR TS = (Outdoor thermal comfort index*)) OR TS = (Human thermal index*))", which enhanced the search scope and made it easier to identify the required articles. The default publication span in the database was set from 1981 to 2023. The literature consisted exclusively of research papers or review articles in English. After reviewing the titles and abstracts, research sites were selected for studies conducted in China and other countries.

3. Results and Analysis

3.1. Analysis of the Study Profile

3.1.1. The Development of Outdoor Thermal Comfort Indicators and Sustainability

Looking at the development of outdoor thermal comfort, it can be observed that as our understanding of outdoor thermal comfort deepens, the number and types of outdoor thermal comfort indicators have also been continuously refined and developed.

Human thermal comfort is a state of consciousness indicating satisfaction with the thermal environment [17]. This concept is used to assess residents' satisfaction with indoor environments. Subsequently, in the study of outdoor thermal comfort, this concept has also been extended [18]. Therefore, the accuracy of understanding the concept of outdoor thermal comfort directly affects the effectiveness and degree of improvement in evaluating the outdoor thermal environment. Outdoor thermal comfort indicators effectively quantify human outdoor thermal perceptions and evaluate the outdoor thermal environment. After over a century of research in human outdoor thermal comfort, 165 thermal comfort rating indicators have been devised to elucidate the relationship between human thermal sensations and the environment [19].

Initial thermal comfort indicators were devised to ensure the safety of workers and military personnel operating under extreme climatic conditions [20]. By analyzing the climatic impact on human thermal sensation using these indicators, guidelines for the relevant personnel activities were established. Theoretically, most thermal comfort indicators utilize regression analyses of meteorological parameters on human thermal sensations to quantify outdoor thermal sensations in various climatic conditions. The following indexes are used for hot environments: wet-bulb globe temperature (WBGT) [21], the discomfort index (DI) [22], the heat stress index (ITS) [23], the heat index (HI) [24], etc. In addition, the following indexes are used to assess cold environments: the wind chill index (WCI) [25], wind chill equivalent temperature (WCET) [26], perceived temperature (PT) [27], and the required clothing insulation index (IREQ) [28]. While these indexes involve fewer parameters and allow for rapid computation of results, their usage is often constrained by geographic and climatic conditions. In reality, their applicability is highly limited. Considering that indexes capable of assessing outdoor thermal comfort under specific climate conditions cover too few scenarios, there has been a continuous effort to develop outdoor thermal comfort indexes suitable for various environmental conditions, such as the temperature–humidity index (THI) [29].

Research on thermal comfort indicators has progressively deepened, leading to a more in-depth understanding of the field. Concurrently, numerous indicators have been devised to quantitatively evaluate thermal comfort under extremely cold and hot conditions [30]. In 1923, Houghten proposed the concept of effective temperature [31], which evolved into the current standard effective temperature (SET*) after several amendments [32]. In 1970, Fanger introduced the thermal balance equation to quantify human thermal comfort by employing the predicted thermal sensation vote (PMV) to reflect human thermal sensations [33]. In 1987, Mayer et al. proposed the concept of physiological equivalent temperature (PET) using the Munich human body heat balance model (MEMI) [34] and the Gagge two-node model [35]. They also developed a modified physiological equivalent temperature (mPET) as an extension of PET. In 2002, Fiala et al. created a comprehensive thermal climate indicator model by applying a multi-node thermoregulation model [36]. Through iterative calculations using this model, the dynamic variations in human thermal sensation over the physical exposure time were accurately depicted.

Furthermore, some studies employ regression analysis to establish the relationship between thermal sensation and environmental parameters. These studies also investigate the interaction of environmental factors on outdoor thermal comfort to assess human thermal perception in outdoor settings [37–41]. When assessing human thermal comfort, it is imperative to take into account not only environmental factors but also subjective elements such as metabolic rate and clothing insulation. These influencing variables have been incorporated into multiple linear regression equations [42,43].

In summary, outdoor thermal comfort indicators have evolved from initial linear indicators to empirical indicators, and ultimately to mechanistic indicators. Concurrently, the outdoor environments to which these indicators apply have shifted from single cold or hot conditions to encompass a variety of meteorological scenarios. Additionally, outdoor thermal comfort indicators have progressed from linear indicators that solely consider environmental parameters to mechanistic indicators that incorporate both environmental and physiological parameters. It is worth noting that mechanistic indicators are established based on the human body of thermal equilibrium, meaning that over time, the heat exchange between the human body and the surrounding environment will reach a state of thermal equilibrium eventually [44,45]. In reality, due to the heat exchange between the human body and the surrounding environment, outdoor thermal comfort is in a constantly changing state [46,47]. Therefore, in order to accurately predict outdoor thermal comfort under different environmental conditions [48], various models have been developed, such as the Fiala model [49], Tanabe model [50], UCB model [51], and ThermoSEM model [52]. These models can be used not only to evaluate outdoor thermal comfort in steady-state environments but also in non-uniform and transient environments [53,54].

With the emergence of new research methods such as neural networks and AI technology, it is anticipated that outdoor thermal comfort indicators will continue to evolve. This provides a theoretical foundation for accurately predicting outdoor thermal comfort in complex urban environments, thereby effectively reducing human heat stress in urban outdoor spaces, and ultimately contributing to the construction of a sustainable and healthy city.

3.1.2. Types of Outdoor Thermal Comfort Indicators

This study investigated the progress of outdoor thermal comfort indicators for categorization purposes. Lai et al. categorized outdoor thermal comfort models into mechanistic and empirical types based on their definitions and developmental approaches [55]. Coccolo et al. classified outdoor thermal comfort models into three classes based on their physical variables and climatic suitability, including those based on human energy balance, empirical data, and linear equations [56]. Therefore, based on the formulas and influencing factors of various outdoor thermal comfort indexes, this paper categorizes outdoor thermal comfort indicators into three types: linear indicators based on cold and hot sensation (linear indicators), mechanistic indicators based on the thermal equilibrium of human body (mechanistic indicators), and empirical indicators based on subjective and objective assessments (empirical indicators). The classification of outdoor thermal comfort indicators is shown in Table 1.

Table 1. Nomenclature and units of specialized terminology and acronyms.

Type	Abbreviation	Index	Unit
Linear indicators based on cold and hot sensation	AT [57]	Apparent Temperature	°C
	CI [58]	Comfort Index	°C
	DI [22]	Discomfort Index	°C
	ET [32]	Effective Temperature	°C
	ESI [59]	Environmental Stress Index	°C
	H [60]	Humidex	°C
	HI [61]	Heat Index	°C
	HSI [62,63]	Heat Strain Index	–
	ITS [23]	Index of Thermal Stress	W
	PE [64]	Cooling Power Index	$W{\cdot}m^{-2}$
	PSI [65]	Physiological Strain Index	°C
	RSI [66]	Relative Strain Index	–
	THI [24,67]	Temperature Humidity Index	°C
	THSW [68]	Temperature Humidity Sun Wind	°C
	WBGT [21]	Wet-Bulb Globe Temperature Index	°C
	WCI [69]	Wind Chill Index	$W{\cdot}m^{-2}$
	T_{WC} [70]	Wind Chill Temperature	°C
Index based on the thermal equilibrium of human body	COMFA [71]	COMfort formula	$W{\cdot}m^{-2}$
	ETU [72]	Universal Effective Temperature	°C
	HL [73]	Heat Load Index	$W{\cdot}m^{-2}$
	HTCI [74]	Outdoor Human Thermal Comfort Index	$W{\cdot}m^{-2}$
	ITS [23,75]	Index of Thermal Stress	W
	PHS [76,77]	Predicted Heat Strain	—
	mPET [78]	Modified Physiological Equivalent Temperature	°C
	OUT_SET* [79,80]	Standard Effective Temperature for Outdoor	°C
	PMV [33]	Predicted Mean Vote	—
	PET [81,82]	Physiologically Equivalent Temperature	°C
	PT [83]	Perceived Temperature	°C
	SET* [35,84]	Standard Effective Temperature	°C
	STI [85]	Subjective Temperature Index	—
	UTCI [86]	Universal Thermal Climate Index	°C
	IREQ [28,87]	Required Clothing Insulation	$m^2{\cdot}K{\cdot}W^{-1}$
Empirical indicators based on subjective and objective evaluations	ASV [40,88]	Actual Sensation Vote	—
	FOCI [89]	Turkish Outdoor Comfort Index	—
	GOCI [90]	Global Outdoor Comfort Index	—
	IZA [38]	Thermal comfort Index for Cities of Arid Zones	—
	MOCI [30]	Mediterranean Outdoor Comfort Index	—
	TSV [91]	Thermal Sensation Vote	—
	TSI [92]	Tropical Summer Index	°C

Mechanistic indicators are established on the basis of the interaction and equilibrium between the human body and its surrounding environment. The thermal energy balance equation of the human body encompasses two major categories of elements: physiological conditions and environmental parameters. It encapsulates various indicators, such as physiological equivalent temperature (PET), modified physiological equivalent temperature (mPET), the universal thermal climate index (UTCI), the predicted mean vote (PMV), standard effective temperature (SET*), outdoor standard effective temperature (OUT_SET*), perceived temperature (PT), the thermal stress index (ITS), the comfort A formula (COMFA), the subjective temperature index (STI), the heat load index (HL), the human thermal comfort index (HTCI), and universal effective temperature (ETU).

Linear indicators define outdoor thermal comfort as a function that includes environmental parameters, with little consideration for the impact of human physiology, behavior, psychology, and other factors. These include indicators such as wet-bulb globe temperature (WBGT), the temperature humidity index (THI), the discomfort index (DI), the comfort index (CI), the thermal index (HI), the humidity index (Humidex), apparent temperature (AT), wind cold temperature (WCT), the wind cold index (WCI), the combined effects of sun, wind, humidity, and temperature (THSW), equivalent temperature (ET), the relative strain index (RSI), the heat stress index (HSI), and the physiological strain index (PSI).

Empirical indexes quantify the outdoor thermal sensation of specific populations at particular locations by combining outdoor environmental parameters with subjective questionnaire surveys [12]. These include indicators such as actual thermal sensation vote (ASV), thermal sensation vote (TSV), the Turkish outdoor thermal comfort index (TOCI), the Mediterranean outdoor thermal comfort index (GOCI), and the arid urban outdoor thermal comfort index (IZA).

3.1.3. Changes in the Annual Number of Publications between China and Other Countries

To track the evolution of research on outdoor thermal comfort indicators, the annual publication count serves as a key metric. Through an initial search on Web of Science, 2040 articles were yielded. Upon screening, 177 articles focused on the application of these indicators in China and 169 addressed their utilization in other countries, summing up to 346 papers incorporated into this study. (For the purpose of summary, the 17 papers published on China from January to May 2023 are not included in Figure 1). The annual article count changes from China and other countries are shown in Figure 1.

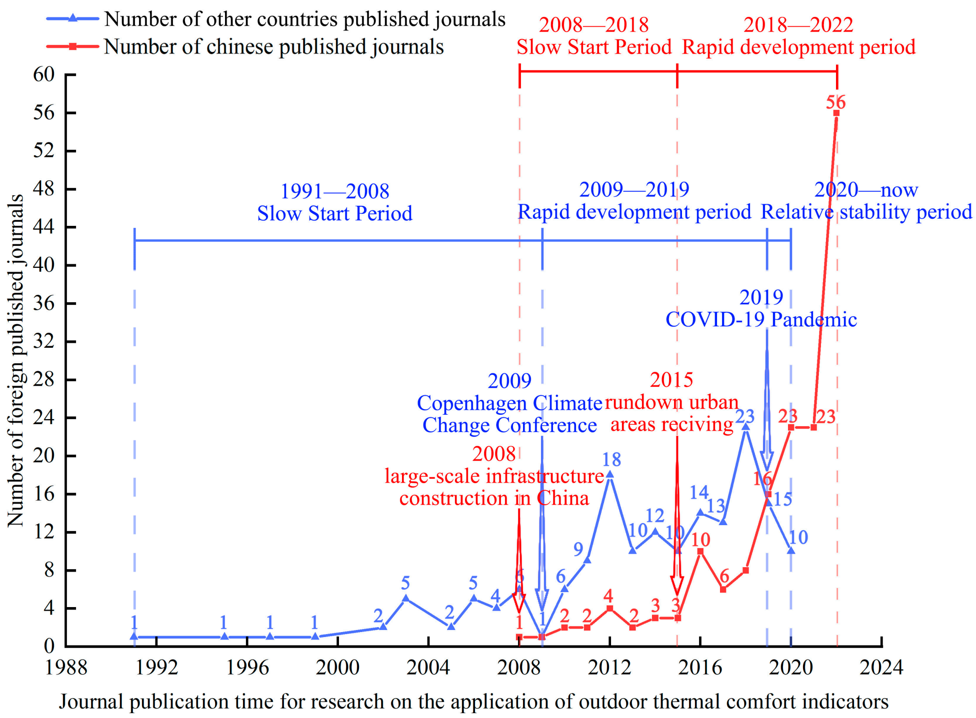


Figure 1. Comparative analysis of the number of papers on applied outdoor thermal comfort indexes between China and other countries.

Looking at the development stages of outdoor thermal comfort index application research in China and other countries, it can be traced back to 1991 for other countries. Due to the rapid urbanization process in developed countries, the impact of urban heat islands on human thermal stress was evident earlier [93]. Therefore, the period from 1991 to 2008 is categorized as a slow start-up phase. Since the Copenhagen Climate Change Conference in 2009, the deterioration of urban outdoor environments due to global warming has received increasing attention from various sectors. Hence, the period from 2009 to 2018 is classified as a period of rapid development [94]. After the outbreak of the COVID-19 pandemic, outdoor activities significantly decreased, leading to a relative decline in research on outdoor thermal environments compared to the period of rapid development. However, it has remained stable. Therefore, the period after 2019 is categorized as a relatively stable phase [95].

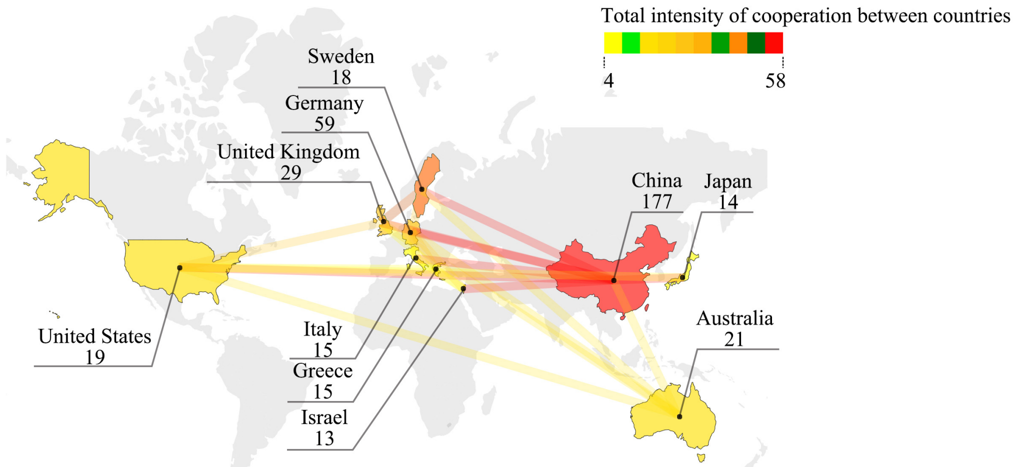
Based on the results retrieved from the Web of Science database, China began publishing papers in this field in 2008. Since then, there have been roughly two phases. Following the extensive infrastructure investments initiated by China in 2008, the urbanization process in China significantly accelerated [96]. Chinese researchers showed increasing attention to the application of outdoor thermal comfort indexes. Therefore, the period from 2008 to 2015 is categorized as a slow start-up phase. Due to policies supporting urban renewal in China, the urbanization rate has once again surged and continues to thrive since 2016 [97]. Benefiting from the Chinese government's strict control measures, the COVID-19 outbreak was brought under initial control within a very short period after its onset [98]. This provided an opportunity for researchers to engage in studies related to outdoor thermal comfort. For example, there have been studies regarding the impact of personal protective equipment such as masks on outdoor thermal comfort [98–101]. Therefore, the research in China during the pandemic was not significantly impacted by external factors. In summary, the period from 2016 to 2022 can be classified as a period of rapid development.

Therefore, in the field of applying outdoor thermal comfort indexes, China has a higher publication count compared to other countries. However, in terms of the timeline of publications, other countries started their research in this field earlier, have a longer research history, and a more mature development trajectory than China.

3.1.4. Distribution and Cooperation of Major International (Regional) Institutions

Collaboration intensity refers to the proportion of published works affiliated with more than one country compared to the total number of publications from that country [102]. This typically reflects the level of research collaboration between different countries and regions. In this study, the cooperation intensity of countries publishing over 10 papers were analyzed to comprehend their research status and collaborative relationship. Figure 2 illustrates the number of publications and the status of collaboration worldwide. While China has led the number of publications on applied research concerning outdoor thermal comfort indicators, Germany has the highest citation count per article in this domain. In terms of collaboration intensity, China exhibits strong research ties with other countries, with the highest cooperation intensity. Geographically, among the top 10 countries, Europe constitutes 50%, Asia 30%, and both North America and Australia contribute 10% each. Predominantly, countries spearheading research on the outdoor thermal comfort index are situated in economically affluent, highly urbanized regions such as Europe, the United States, and the Asia-Pacific. Although China has the highest publication output in the field of outdoor thermal comfort index application research and maintains the closest collaborations with other countries, it has the lowest average citation count among the top ten countries in terms of publication volume. Therefore, there is room for improvement in the influence of research outcomes in this field for China.

This study evaluated publications from institutions that conducted applied research on outdoor thermal comfort indicators. The objective was to determine the influence of the major research institutions in China and other countries in this research domain. Furthermore, centrality is the ability to act as a mediator in the entire network. In the network structure, nodes with centrality greater than 0.1 represent positions of greater importance [103]. Among the top 10 global institutions by publication count, nine are European, one is Asian, and Germany contains the top three. Firstly, publication count serves as the primary metric for the influence among these institutions, exceptions include the University of Freiburg (34 articles) and the Chinese Academy of Sciences (16 articles). The leading 10 institutions from China and internationally were classified into two categories based on their article counts: $5 \leq N < 10$ and $10 \leq N < 15$. In addition, when institutions fall within the same publication range, and a mediated centrality over 0.1 [104], the average citation count is used as a secondary prioritized reference metric. Figure 3 presents the process of ranking the influence of major research institutions in China and other countries on the application of outdoor thermal comfort indicators.



Country name	The number of publications by countries	The intensity of Cooperation	The number of total citations	The average citations for per article
China	177	58	5155	29.12
Germany	59	30	9137	154.86
United Kingdom	29	30	2629	90.66
Australia	21	19	1920	91.43
United States	19	16	1711	90.05
Sweden	18	12	1887	104.83
Italy	15	9	1143	76.2
Greece	15	9	1135	75.67
Japan	14	7	509	36.35
Israel	13	4	1615	124.23

Figure 2. Main countries for published research on the application of outdoor thermal comfort indicators.

The University of Freiburg emerges prominently with the highest publication count at 34, indicating a betweenness centrality of 0.34 and an average citation per publication of 196.53. This position makes it the most influential institution in applied research on outdoor thermal comfort indicators. Meanwhile, the Dortmund University of Technology has the highest publication output in the range of $10 \leq N < 15$, with a total of 12 papers. Additionally, it exhibits a betweenness centrality of 0.12. The institution's average application count per paper is 92.17, making it the second most influential institution in international research on the application of outdoor thermal comfort indexes. Loughborough University, holding a top position in the $5 \leq N < 10$ publication category and having a betweenness centrality of 0.21, is the third most influential entity in international research on outdoor thermal comfort indicators. The top 10 influential international research institutions on outdoor thermal comfort applications are listed in Table 2.

Based on the aforementioned criteria, among the top 10 Chinese research institutions, the Chinese Academy of Sciences possesses the highest number of publications in China, followed by the City University of Hong Kong, and the University of Hong Kong ranks third.

Upon analyzing the top 10 institutions employing outdoor thermal comfort indicators in China and other countries, it was observed that while China has marginally more publications in this domain, international institutions demonstrated a significantly higher average citation count per paper than that of Chinese counterparts. Therefore, Chinese research institutions should seek to enhance their research in this area. The top 10 influential research institutions in China on outdoor thermal comfort application research are listed in Table 3.

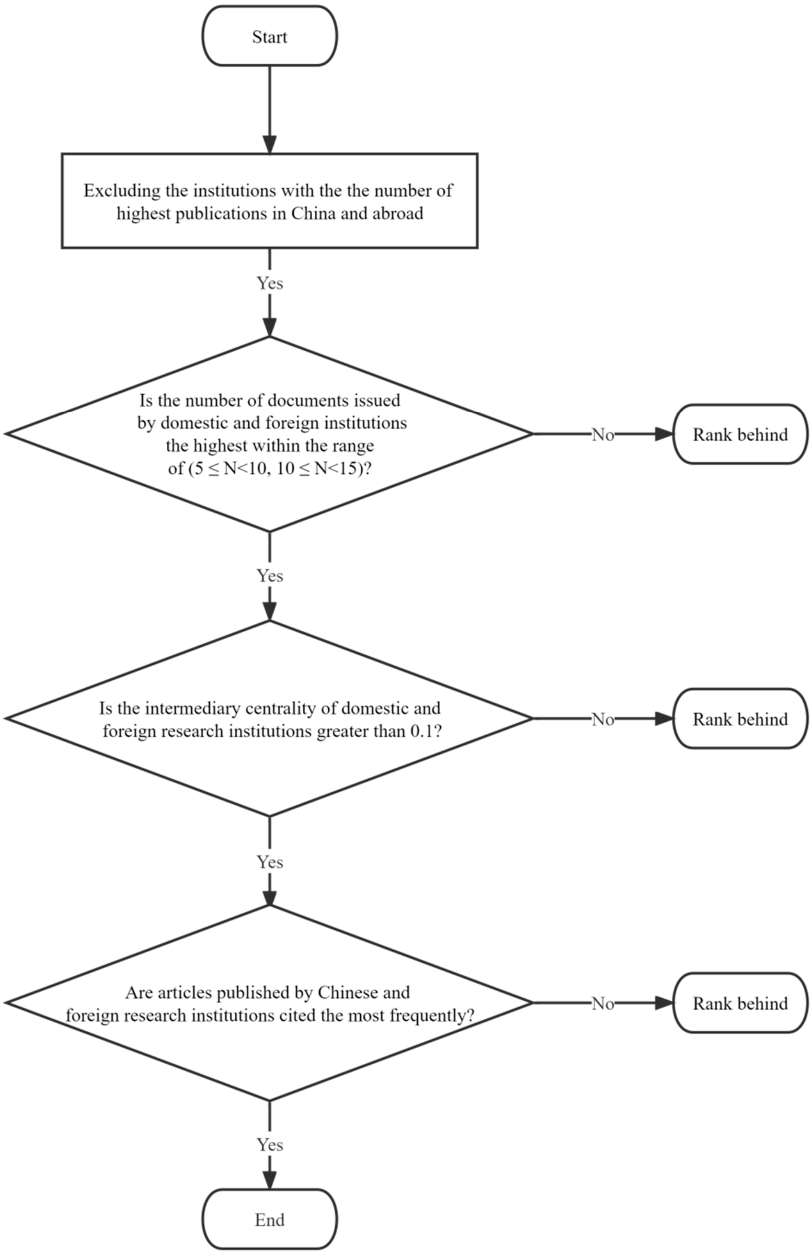


Figure 3. Flow chart illustrating the ranking of research institution influence in the field of outdoor thermal comfort indicator application in China and other countries.

Table 2. Top 10 international research institutions ranked by research influence in the application of outdoor thermal comfort indicators.

Top 10 International Research Institutions in Outdoor Thermal Comfort Application Research	Number of Publications	Centrality	Total Number of Citations	Number of Citations per Article
University of Freiburg	34	0.34	6682	196.53
Dortmund University of Technology	12	0.12	1106	92.17
Loughborough University	6	0.21	1388	231.33
Tel Aviv University	7	0.11	1375	196.43
Lund University	6	0.04	965	160.83
National and Kapodistrian University of Athens	9	0	618	68.67
Sapienza University Rome	9	0.01	510	56.67
Deutscher Wetterdienst	9	0.05	439	48.78
Polish Academy of Sciences	5	0.03	930	186
Universidade Tecnologica Federal do Parana	5	0.03	531	106.2

Table 3. Top 10 Chinese research organizations ranked by influence in applied research on outdoor thermal comfort indicators.

Top 10 Chinese Research Institutions in Outdoor Thermal Comfort Application Research	Number of Papers	Centrality	Total Number of Citations	Number of Citations per Article
Chinese Academy of Sciences	16	0.22	233	14.56
City University of Hong Kong	11	0.51	490	44.55
University of Hong Kong	14	0.17	370	26.43
Northwest A&F University	14	0.00	319	22.79
Harbin Institute of Technology	15	0.02	182	12.13
Chinese University of Hong Kong	7	0.32	853	121.86
Guangzhou University	8	0.33	144	18
Sun Yat Sen University	8	0.51	122	15.25
Tongji University	8	0.12	93	11.63
Hong Kong Polytechnic University	9	0.07	222	24.67

In evaluating climate distribution, the majority of the top 10 research institutions focusing on outdoor thermal comfort indicator application in China and other countries are situated in warmer climatic zones [105]. Figure 4 presents the distribution of major institutions in China and other countries across various climate zones concerning applied research on outdoor thermal comfort indicators. Institutions from Germany, the UK, and Sweden belong to the marine west coast (Cfb) climate zone, whereas those from Italy, Greece, and Israel are in the Mediterranean climate zone (Csa). Brazilian institutions fall under the tropical savanna climate zone (Aw), and Polish institutions fall under the humid continental climate zone (Dfb).

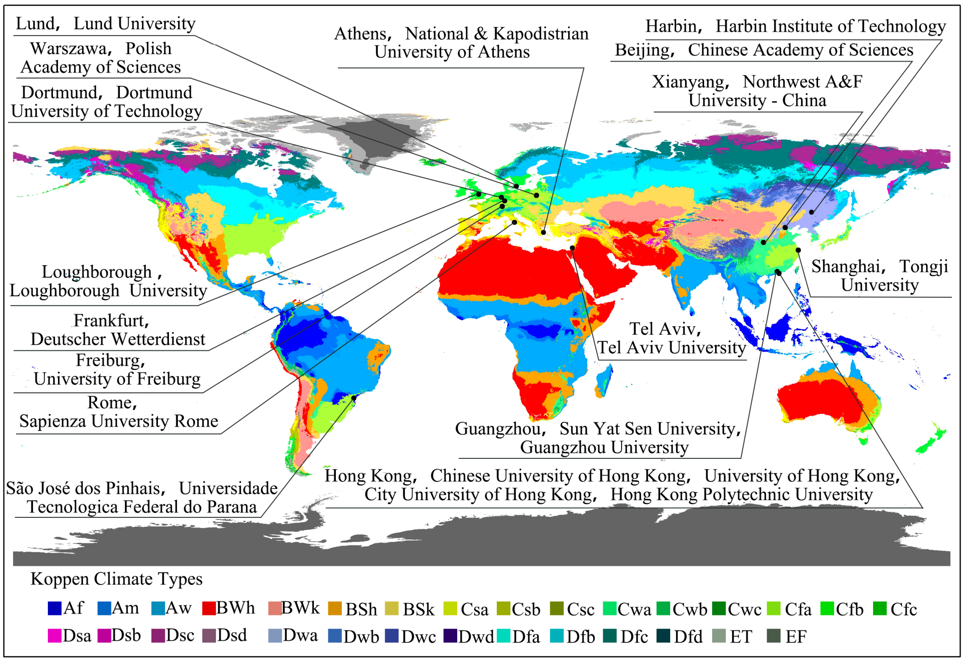


Figure 4. Distribution of the main institutions in applied research on outdoor thermal comfort indexes.

Among the top 10 applied research institutions on outdoor thermal comfort indicators in China, Beijing's institutions fall under the monsoon-influenced continental (Dwa/BSk) climate zone; Harbin's institutions are in the monsoon-influenced, humid continental (Dwa) climate zone; Xianyang's institutions span both the semi-arid (BSk) and humid subtropical (Cwa) climate zones; and institutions in Shanghai, Hong Kong, and Guangzhou are all situated within the humid subtropical (Cfa) climate zone.

Among the top 10 international institutions focusing on outdoor thermal comfort, 80% are situated in the marine west coast (Cfb) and Mediterranean (Csa) climate zones.

Conversely, among the top ten research institutions in the field of outdoor thermal comfort in China, 60% of them are located in the humid subtropical (Cfa) climate zone. The geographical distribution of institutions may be related to the climate conditions in the marine west coast (Cfb), Mediterranean (Csa), and humid subtropical (Cfa) regions. Compared to other climate zones, these areas often endure more extended periods of hot weather, more diverse climates, and higher population convergence.

3.1.5. Main Authors from China and Other Countries

This study evaluated the contributions of the top 10 authors in the realm of outdoor thermal comfort indicator application research, with a focus on comparing the influence of authors from China with those from other nations and exploring their collaborative patterns. The assessment commenced by counting each author's publications, followed by them being categorized into three intervals for comparative analysis: $0 < N \leq 5$, $5 \leq N < 10$, and $10 \leq N < 15$. The primary metric used for the comparison was the number of articles. Furthermore, when the number of publications for authors falls within the same range, comparing the average citation count per paper for each author allows us to assess their level of influence. The process of ranking the influence of the main authors in the applied research on outdoor thermal comfort indicators in China and other countries is depicted in Figure 5.

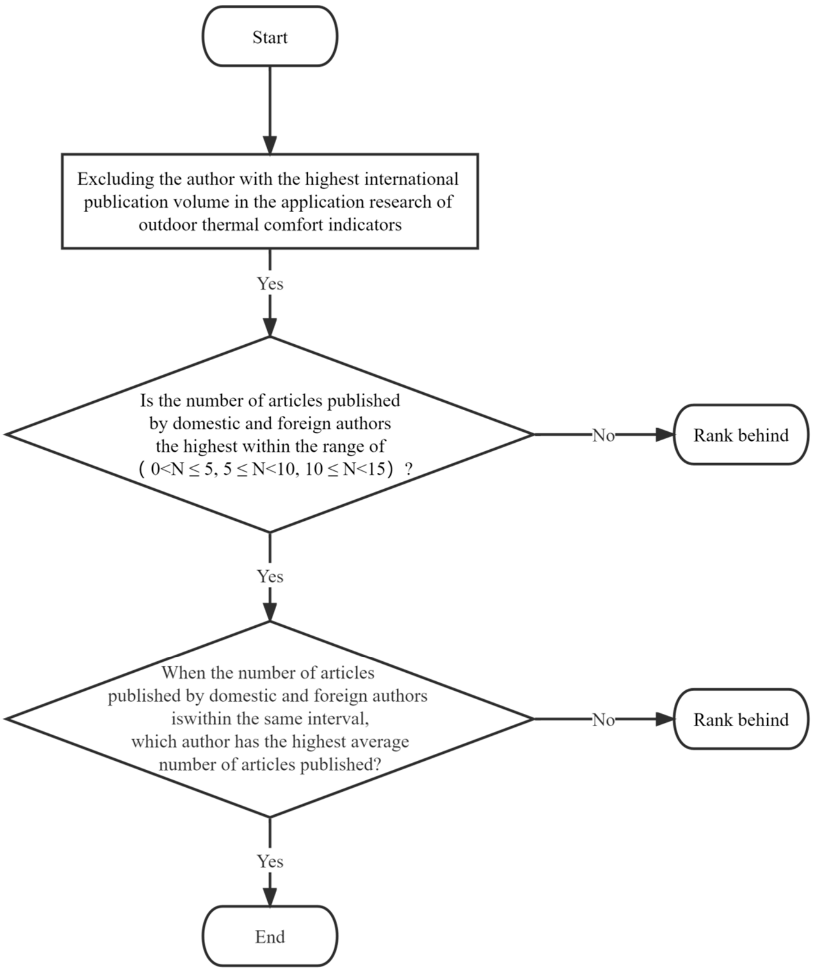


Figure 5. Flowchart of author's influence ranking.

In terms of the influence of authors in the field of applying outdoor thermal comfort indexes in China, Bo, Hong has the highest number of publications, thus being considered the most influential author in this field in China. Lam, Cho Kwong Charlie comes second in terms of publication volume, and is regarded as the second most influential author in this field in China. Lin, Tzu-Ping has the highest citation count within the range of $0 < N \leq 5$ publications, hence is considered the third most influential author in this field in China. The top 10 influential authors of outdoor thermal comfort application research in China are presented in Table 4.

Table 4. Top 10 influential Chinese authors in applied research on outdoor thermal comfort indicators.

Top 10 Influential Chinese Authors of Applied Research on Outdoor Thermal Comfort Indicators	Institutions of the Chinese Authors of the Applied Study of Outdoor Thermal Comfort Indicators	Number of Papers	Total Number of Citations	Number of Citations per Article
Bo Hong	Northwest A&F University	13	319	24.54
ChoKwong Charlie Lam	Sun Yat Sen University	8	122	15.25
Tzu Ping Lin	National Formosa University	4	988	247
Edward Ng	Chinese University of HongKong	4	813	203.25
Dayi Lai	Shanghai Jiao Tong University	3	276	92
C Y Jim	University of HongKong	4	142	35.5
Yongxin Xie	HongKong Polytech University	4	138	34.5
Jian Hang	Sun Yat Sen University	3	57	19
Hong Jin	Harbin Institute of Technology	4	66	16.5
Xin Chen	Harbin Institute of Technology	4	50	12.5

In terms of global contributions to the application of outdoor thermal comfort indicators, Andreas Matzarakis had the highest number of publications, rendering him the most influential authority on the topic. Gerd Jendritzky, holding publications in the range of $5 < N \leq 10$ and possessing the highest average citations per paper in this bracket, is recognized as the second most influential figure internationally. Peter Broede, also with publications in the $5 < N \leq 10$ range, and the second-highest average citations within this range, is deemed the third most influential author in the international domain. Table 5 displays the top 10 influential authors of international research on outdoor thermal comfort applications.

Table 5. Top 10 influential international authors in applied research on outdoor thermal comfort indicators.

Top 10 International Authors of Influential Research on the Application of Outdoor Thermal Comfort Indicators	Institutions of International Authors in Applied Studies on Outdoor Thermal Comfort Indicators	Number of Papers	Total Number of Citations	Number of Citations per Article
Matzarakis, Andreas	University of Freiburg	30	4065	135.5
Jendritzky, Gerd	University of Freiburg	8	1909	238.625
Broede, Peter	Dortmund University of Technology	6	1106	184.3
Mayer, Helmut	University of Freiburg	6	955	156.17
Blazejczyk, Krzysztof	Polish Academy of Sciences	6	976	122
Salata, Ferdinando	Sapienza University Rome	8	779	97.375
Golasi, Lacopo	Sapienza University Rome	8	365	45.625
Havenith, George	Loughborough University	5	1328	265.5
Vollaro, Andrea De Lieto	Sapienza University Rome	5	629	125.8
Potchter, Oded	Tel Aviv University	5	613	122.6

In addition, in bibliometric studies, the number and thickness of collaborative network connections among authors can also reflect the degree of academic exchange. Gerd Jendritzky, Krzysztof Blazejczyk, and Peter Broede form a collaborative network. Lacopo Golasi and Ferdinando Salata also have a close collaboration. In contrast, only the Chinese scholar Lin, Tzu-Ping has close academic interactions with Andreas Matzarakis.

Therefore, scholars from other countries have closer academic exchanges compared to Chinese scholars.

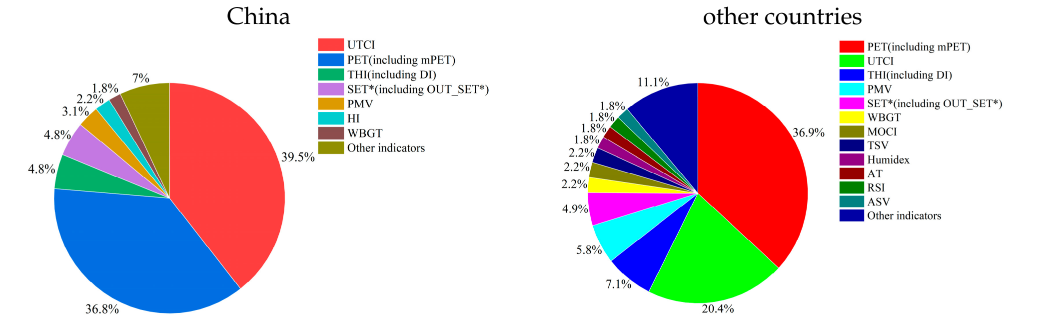
The research findings indicate that among the top ten authors in the field of outdoor thermal comfort index application research in both China and other countries, scholars from other nations tend to have a higher publication count compared to Chinese scholars. Additionally, the average citation count per paper for these international scholars is generally higher than that of Chinese scholars. Moreover, in comparison to Chinese scholars, authors from other countries have a more extensive academic collaboration network and a more mature network. Therefore, Chinese scholars are expected to strengthen their interactions with scholars from both domestic and international arenas in this field, aiming to establish a more mature collaborative network.

3.1.6. Frequency of Indicators Used by China and Other Countries

This study sought to examine the similarities and differences in the application of outdoor thermal comfort indicators in China and other countries. To achieve this, we analyzed titles and keywords from the literature sourced from the Web of Science, quantifying the frequency of distinct indicators utilized. Table 6 presents the statistical results for the frequency of application of outdoor thermal comfort indicators in China and other countries.

Table 6. Statistics on the frequency analysis of outdoor thermal comfort indicator usage in China and other countries.

Utilization Frequency of Key Outdoor Thermal Comfort Indicators in China and Other Countries



In this study, after conducting a statistical analysis of outdoor thermal comfort indexes used in research from both China and other countries, with a frequency of four or more occurrences (indexes with a frequency of less than four were categorized under "other indices"), it was found that among the top five most frequently used indexes in other countries, they are in the following order: PET (including mPET), UTCI, THI (including DI) [67], and PMV, SET* (including OUT_SET*). In China, the top five most frequently used outdoor thermal comfort indexes are in the following order: UTCI, PET (including mPET), THI (including DI), and SET* (including OUT_SET*). Therefore, in this study, the top five most frequently used indexes in both China and other countries are considered commonly used indicators.

Based on statistical results, when examining the similarity in the frequency of use of the top five indicators in China and other countries, both share the same top five outdoor thermal comfort indicators, with PET and UTCI being the top two in terms of frequency of use. However, looking at the differences in the frequency of use of the top five indicators between China and other countries, the top five outdoor thermal comfort indicators used in other countries account for 75.11% of their total usage frequency, while in China, the top five indicators make up 89.04% of the total usage frequency of outdoor thermal comfort indicators. Among these, PET and UTCI, which are the top two indicators in both China and other countries, account for 76.31% and 57.33% of their respective total usage frequency of outdoor thermal comfort indicators. This indicates that compared to other countries, China has a higher proportion of usage for commonly used indicators.

Furthermore, in terms of the similarity in the types of outdoor thermal comfort indicators used in China and other countries, both utilize THI (including DI) and WBGT as linear indicators. Additionally, both use PET (including mPET), UTCI, PMV, and SET* (including OUT_SET*) as mechanistic indicators. In terms of the differences in the types of outdoor thermal comfort indicators used in China and other countries, in the category of linear indicators, other countries use HUMIDEX, AT, and RSI, while China uses HI. In the category of empirical indicators, other countries tend to use TSV and ASV more frequently. In comparison, Chinese researchers use empirical indicators less frequently, and they were not included in the statistical scope. Therefore, researchers in other countries use a significantly larger number of indicators compared to their Chinese counterparts, especially in the categories of linear and empirical indicators. This indicates that in other countries, the development of outdoor thermal comfort indicators is more comprehensive, and the range of types used is more extensive.

3.2. Analysis of Research Findings

3.2.1. Outdoor Thermal Comfort Indicator Application Themes in China and Other Countries

The study conducted a review of outdoor thermal comfort research by collecting review articles and journal papers on the application of thermal comfort indexes from Web of Science. It systematically analyzed the research focuses on outdoor thermal comfort in China and other countries under different types of indexes, thereby identifying the similarities and differences in the research themes of thermal comfort indexes between the two sides. Table 7 presents the application themes corresponding to each type of outdoor thermal comfort indicator in China and other countries.

From the application themes of outdoor thermal comfort indicators in other countries, firstly, linear indicators encompass six research topics: “Assessing Outdoor Human Thermal Comfort”, “Impact of Outdoor Environmental Elements on Outdoor Thermal Comfort”, “Measuring Outdoor Human Thermal Stress”, “Evaluating Outdoor Environmental Conditions”, “Assessing the Applicability of Outdoor Thermal Comfort Indicators”, and “Improving Research Methods for Outdoor Thermal Comfort Indicators”. Secondly, mechanistic indicators cover six research topics: “Assessing Outdoor Human Thermal Comfort”, “Improving Research Methods for Outdoor Thermal Comfort Indicators”, “Impact of Outdoor Environmental Elements on Outdoor Thermal Comfort”, “Evaluating Outdoor Environmental Conditions”, “Measuring Outdoor Thermal Stress”, and “Assessing the Applicability of Outdoor Thermal Comfort Indicators”. Lastly, empirical indicators include four research topics: “Assessing Outdoor Human Thermal Comfort”, “Measuring Outdoor Human Thermal Stress”, “Impact of Outdoor Environmental Elements on Outdoor Thermal Comfort”, and “Evaluating the Applicability of Outdoor Thermal Comfort Indicators”.

In terms of research focus on the application of outdoor thermal comfort indicators in China, firstly, for linear indicators, there are three research topics: “Assessing Outdoor Human Thermal Comfort”, “Measuring Outdoor Human Thermal Stress”, and “Impact of Outdoor Environmental Elements on Outdoor Thermal Comfort”. Secondly, for mechanistic indicators, there are six research topics: “Assessing Outdoor Human Thermal Comfort”, “Impact of Outdoor Environmental Elements on Outdoor Thermal Comfort”, “Evaluating the Applicability of Outdoor Thermal Comfort Indicators”, “Improving Research Methods for Outdoor Thermal Comfort Indicators”, “Measuring Outdoor Thermal Stress”, and “Evaluating Outdoor Environmental Conditions”. Thirdly, for empirical indicators, there is one research topic: “Assessing Outdoor Human Thermal Comfort”.

Table 7. Comparison of similarities and differences in outdoor thermal comfort indicator application themes between China and other countries.

Types of Outdoor Thermal Comfort Indicators Used Domestically and Internationally	Differences and Similarities in the Theme of Using Outdoor Thermal Comfort Indicators at Home and Abroad		Example References
Linear indexes based on cold and hot sensations (linear indexes)	similarity	Evaluation of outdoor human thermal comfort	[106–109]
		Measuring outdoor human heat stress	[110–112]
		Impact of outdoor environmental elements on outdoor thermal comfort	[113–118]
	difference	Evaluation of the applicability of outdoor thermal comfort indicators (abroad)	[29]
		Improvement of outdoor thermal comfort index research methodology (abroad)	[119]
		Assessment of outdoor thermal conditions (abroad)	[120,121]
Mechanistic indexes based on the thermal equilibrium of human body (mechanistic indexes)	similarity	Evaluation of outdoor human thermal comfort	[122–126]
		Assessment of outdoor thermal conditions	[127–131]
		Measuring outdoor human heat stress	[132–135]
		Impact of elements of the outdoor thermal environment on outdoor thermal comfort	[136–141]
		Evaluation of the applicability of outdoor thermal comfort indicators	[142–146]
		Improvement of outdoor thermal comfort index research methodology	[147–152]
Empirical indexes based on subjective and objective evaluations (empirical indexes)	similarity	Evaluation of outdoor human thermal comfort	[153–157]
	difference	Measuring outdoor human heat stress (abroad)	[158]
		Evaluation of the applicability of outdoor thermal comfort indicators (abroad)	[159]
		Impact of outdoor environmental elements on outdoor thermal comfort (abroad)	[160,161]

Looking at the similarity in the application of outdoor thermal comfort indicators between China and other countries, firstly, for linear indicators, the research topics include "Assessing Outdoor Human Thermal Comfort", "Impact of Outdoor Environmental Elements on Outdoor Thermal Comfort", and "Measuring Outdoor Human Thermal Stress". Secondly, regarding mechanistic indicators, the application themes in China and other countries are identical, covering "Assessing Outdoor Human Thermal Comfort", "Impact of Outdoor Environmental Elements on Outdoor Thermal Comfort", "Evaluating the Applicability of Outdoor Thermal Comfort Indicators", "Improving Research Methods for Outdoor Thermal Comfort Indicators", "Measuring Outdoor Thermal Stress", and "Evaluating Outdoor Environmental Conditions". Finally, for empirical indicators, both China and other countries are engaged in the application of "Assessing Outdoor Human Thermal Comfort".

Looking at the differences in the application of outdoor thermal comfort indicator research between China and other countries, firstly, in linear indicators, other countries, compared with China, have conducted three more studies on "Evaluating Outdoor Environmental Conditions", "Assessing the Applicability of Outdoor Thermal Comfort Indicators", and "Improving Research Methods for Outdoor Thermal Comfort Indicators". Secondly, in empirical indicators, other countries, compared with China, have conducted three more studies on "Measuring Outdoor Human Thermal Stress", "Impact of Outdoor Environmental Elements on Outdoor Thermal Comfort", and "Evaluating the Applicability of Outdoor Thermal Comfort Indicators".

Therefore, in terms of mechanism indicators, researchers from China and other countries share consistent research themes. However, in terms of linear and empirical indicators, researchers from other countries have conducted more extensive research compared to their

Chinese counterparts. Chinese researchers are expected to strengthen applied research in linear indicators and empirical indicators.

3.2.2. Trends in the Application of Outdoor Thermal Comfort Indicators in China and Other Countries

Keywords provide a comprehensive summary of the core content of an article. This study employed clustering analysis of keywords to investigate the evolution of each cluster from its inception to the retrieval deadline. In CiteSpace 5.7.R5, using the software's timeline visualization feature, we extracted and categorized the predominant keywords within each cluster. The objective was to clarify the trend of outdoor thermal comfort indicator applications in China and other countries.

In the realm of outdoor thermal comfort indicator research in China, studies were organized into 13 keyword clusters. Figure 6 illustrates the research trends in the application of outdoor thermal comfort indicators in China. These encompass #0 thermal mitigation strategies, #1 outdoor thermal sensation, #2 adaptive thermal comfort, #3 land-use metrics, #4 urban performance simulation, #5 bioclimatic design, #6 microclimate, #7 heat stress, #8 thermal adaptation, #9 physiological responses, #10 behavioral adaptation, #11 outdoor thermal environment, and #12 thermal adaptation. Upon analysis, clusters #1, #2, #7, #8, #9, #10, and #12, representing seven keywords, predominantly pertain to the applications of outdoor thermal comfort indicators for the evaluation of human thermal health. Meanwhile, clusters #0, #3, #4, #5, #6, and #11, a set of six keywords, primarily relate to the applications of outdoor thermal comfort indicators within the context of outdoor thermal environment optimization.

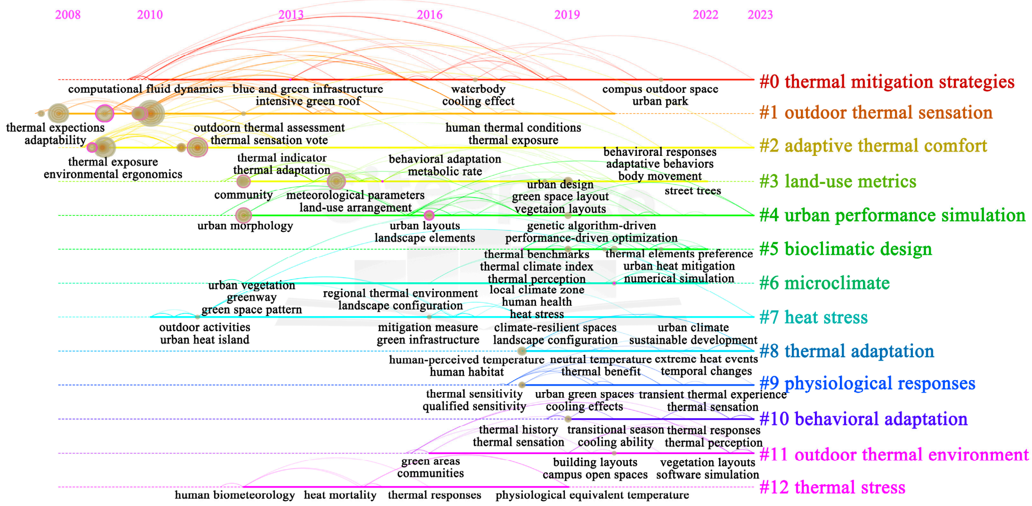


Figure 6. Trends in the application of outdoor thermal comfort indicators in China.

In analyzing the research trends of outdoor thermal comfort indicators in other countries, studies were segmented into 11 key clusters, which included: #0 human heat exposure, #1 climate change, #2 heat wave, #3 urban microclimate, #4 urban heat island, #5 heat adaptation, #6 microclimate, #7 weather perception, #8 urban thermal environment, #9 bioclimatic design, and #10 mitigation strategies. Figure 7 illustrates the research trends in the application of outdoor thermal comfort indicators in other countries. Upon examining three clusters, which included: #0 human heat exposure, #5 heat adaptation, and #7 weather perception, were related to human thermal health evaluations in the context of outdoor thermal comfort indicators. Conversely, the remaining eight clusters, such as #1 climate change, #2 heat wave, #3 urban, #4 urban heat island, #6 microclimate, #8 urban thermal environment, #9 bioclimatic design, #10 mitigation strategies, were summarized to the application of outdoor thermal comfort indicators for optimizing outdoor thermal environments.

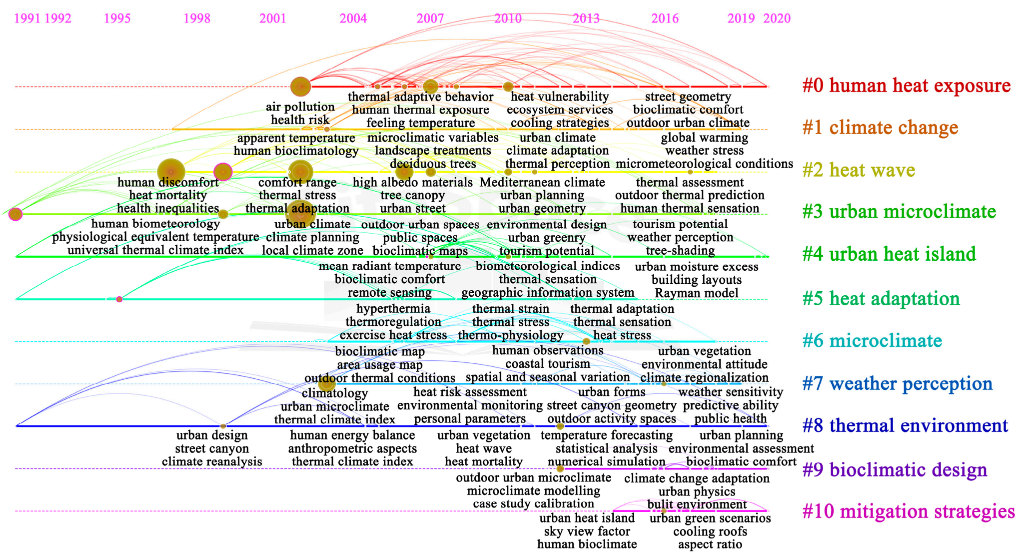


Figure 7. Trends in the application of outdoor thermal comfort indicators in other countries.

Therefore, in summarizing the application trends of outdoor thermal comfort indicators in China and other countries, it was observed that both Chinese and international researchers are conducting studies on the evaluation of human thermal health and the optimization of outdoor thermal environments. However, there are differences in the application trends of outdoor thermal comfort indicators between China and other countries. In the assessment of human thermal health, Chinese researchers emphasize outdoor thermal comfort behavior and psychological factors, while researchers in other countries focus on measuring outdoor human thermal stress. In terms of optimizing the outdoor thermal environment, China emphasizes proposing strategies to improve outdoor thermal conditions, while other countries focus on assessing the status of the outdoor thermal environment. It is worth noting that both Chinese and international researchers have conducted relatively fewer studies on the theoretical expansion of outdoor thermal comfort indicators. For example, outdoor thermal comfort indicators need to consider psychological [162], behavioral [163], social [164], and cultural [165] factors. Furthermore, outdoor thermal comfort indicators need to be adjusted to quantify the outdoor thermal perception of different groups (age, gender, thermal experience, etc.) in various scenarios [166]. Therefore, researchers from both China and other countries are expected to strengthen research on the theoretical expansion of outdoor thermal comfort indicators.

4. Discussion

4.1. Extension of the Theoretical Aspects of Outdoor Thermal Comfort Indicators

Both China and other countries have utilized linear, mechanistic, and empirical indicators. However, there is a need to expand research on the influencing factors of outdoor thermal comfort indicators, their applicability in different climates and populations, and the research methods for outdoor thermal comfort indicators.

4.1.1. Extension of the Theoretical Aspects of Linear Indicators

Linear indicators rely on human thermal sensation to assess the quality of outdoor thermal environments. Among linear indicators, both China and other countries frequently utilize THI (including DI) [67], WBGT [21], HI [24] and HUMIDEX [60]. All of which incorporate physical factors such as air temperature and relative humidity.

As research progresses, some linear indicators have also incorporated physiological factors. For example, the PSI index includes rectal temperature and heart rate, and is used to measure outdoor human thermal stress [111,132]; The ITS index is composed of net radiation Rn, convective radiation C, and body net metabolic heat M-W, which is used to evaluate outdoor thermal conditions [111] and quantify human thermal perception [167,168].

It is worth noting that although equations, such as those proposed by Coccolo et al., which linearly combine many influencing factors of outdoor thermal comfort, are referred to as linear indicators like THI, WBGT, PSI, etc. [56]; In reality, the development of these indicators involves regression analysis of human thermal stress with target parameters [169]. Blazejczyk categorizes outdoor thermal comfort indicators into rational indicators (based on the heat balance equation), empirical indicators (based on objective and subjective strains), and direct indicators (based on direct measurements of environmental variables) [170]. Therefore, building upon this framework, Lai et al. further classify outdoor thermal comfort indicators into two categories based on their definitions and development methods: empirical indicators and mechanistic indicators. Models based on the human heat balance equation are classified as mechanistic indicators, while those based on subjective and objective assessments are classified as empirical indicators. Consequently, these linear indicators should all be categorized as empirical indicators [55,161].

Furthermore, certain linear indicators have demonstrated limitations in their application. For example, THI is only suitable for providing a reliable assessment of outdoor thermal comfort within a narrow range of moderately humid conditions, and it is not accurate for evaluating outdoor thermal comfort in extremely hot or cold conditions [29,60]. While WBGT is widely used to measure outdoor heat stress [116], some studies suggest that it overestimates outdoor heat stress conditions in hot and humid climates [171]. Additionally, determining the critical value of WBGT requires adjustments based on the local body surface area, and instruments used to measure WBGT are often not calibrated. In situations where non-standard sensors are used, this can lead to inaccuracies [172], which contradicts the views of Aghamohammadi et al. [6]. Compared to HSI, PSI is better at assessing heat exposure under high thermal strain conditions [173], but its effectiveness still needs to be validated in women and other age groups [65]. Therefore, there is a need to enhance the applicability of linear indicators for different climate conditions, age groups, and gender groups. It is also important to accurately define and categorize linear indicators, which will facilitate the development of new indicators and their more precise application in evaluating outdoor thermal comfort.

4.1.2. Extension of the Theoretical Aspects of Mechanism Indicators

Mechanism indicators are established on the theoretical foundation of human thermal balance [82,174]. They are formed by combining physical environmental parameters with human physiological parameters [169]. Building upon the work of previous researchers who identified hundreds of influencing factors, Fanger distilled four physical environmental parameters—air temperature, relative humidity, air velocity, and mean radiant temperature—along with two human physiological parameters—clothing insulation and metabolic rate—to construct the predicted mean vote (PMV) model [33]. Subsequent researchers have expanded upon Fanger's indoor human thermal balance model by incorporating mean radiant temperature and air velocity as additional environmental variables, continually developing models that can be applied outdoors [175].

In mechanism indicators, China, like other countries, predominantly employs four indicators: PET (including mPET), PMV, SET* (including OUT_SET*), and UTCI. Among these, PET (including mPET) and UTCI account for more than 50% of the total frequency of usage for outdoor thermal comfort indicators in both cases. This conclusion aligns with the findings of Sharma [12] and Potchter [11]. It is worth noting that although PMV was initially used to assess indoor human thermal comfort controlled by HVAC systems [176], it gradually found applications in the field of outdoor thermal comfort [177,178]. However, numerous studies related to outdoor thermal comfort have confirmed that PMV is not accurate in predicting outdoor human thermal sensation and often overestimates people's actual thermal perception [179–182]. This contrasts with Matzarakis' belief that PMV is well-suited for evaluating outdoor thermal environments in different climates [183]. Nevertheless, PMV can be utilized to measure human heat stress in high-temperature environments [184].

PET is based on the MEMI dual-node energy model [81], while SET* (OUT_SET*) is based on the dual-node model developed by Gagge et al. [32]. These models are steady-state heat transfer models. These indicators are based on the assumption of stable external climatic conditions, prolonged contact between the human body and the environment, and the attainment of thermal equilibrium. However, UTCI is based on the multi-node model developed by Fiala et al. [185]. This model is a dynamic heat transfer model. This indicator is based on the transient sensation of outdoor thermal comfort, with the exchange of energy between the human body and the surrounding environment constantly changing. Although these three indicators are widely used in research related to outdoor thermal comfort, they exhibit certain limitations in the climatic conditions to which they are applicable. For example, OUT_SET* is considered more suitable for warm temperate climates [11], which aligns with the findings of Xi et al. [186] and Zhao et al. [187]. While PET and UTCI are applicable to various climatic zones [12], PET is not suitable for all hot-humid climates, leading to the development of the mPET model [166].

Therefore, in the realm of mechanistic indicators, PMV should not be applied in research related to outdoor thermal comfort. This aligns with the findings of de Freitas, who conducted a comprehensive comparison and evaluation of various outdoor thermal comfort indicators [19]. PET and UTCI are suitable for various climate zones, while OUT_SET* performs well in warm temperate climates. However, as mechanistic indicators incorporate a more comprehensive range of influencing factors, the computational models used become increasingly complex. For example, based on the Stolwijk model, the Fiala model [49,188,189], Tanabe model [50], UCB model [51,190], ThermoSEM [191,192], and JOS-2 [193] have been developed to assess outdoor thermal comfort in non-uniform and transient climatic environments. However, these models often entail complex computations and demand high computational resources. In summary, there is currently a lack of an outdoor thermal comfort indicator that can accurately predict outdoor thermal comfort outcomes, has a straightforward calculation method, and can be used across various climatic conditions [55,194]. Therefore, striking a balance between calculation accuracy and indicator usability is an issue worth considering.

4.1.3. Extension of the Theoretical Aspects of Empirical Indicators

Empirical indexes typically employ regression analysis to establish the mathematical relationship between environmental parameters and subjective thermal sensations [195]. The factors impacting outdoor thermal comfort generally include four objective variables: air temperature, relative humidity, wind speed, and mean radiant temperature (Ta, RH, Va, Tmrt), as well as two subjective variables: clothing insulation and metabolic rate (Iclo, M).

It is worth noting that most empirical indicators only include outdoor environmental parameters, and empirical indexes that include subjective variables are rare [91]. The most commonly used empirical indicators in both China and other countries are TSV and ASV. However, these types of indicators often only calculate outdoor thermal comfort in local climates. In other words, they may not be applicable in different climatic regions. Therefore, expanding the application of empirical indicators in different climatic regions is particularly necessary.

Salata et al. developed the Mediterranean outdoor comfort index (MOCI) to predict local residents' perception of outdoor thermal comfort [37]; Canan et al. developed the Turkish outdoor comfort index (TOCI) to predict local residents' perception of outdoor thermal comfort under hot conditions [89]; Golasi et al. summarized regression models for subjective and objective evaluations from around the world and derived the global outdoor comfort index (GOCI) [90]; Angelica Ruiz et al. proposed the oasis city outdoor comfort index (IZA) for predicting outdoor thermal comfort in arid climate conditions [38]. The derivation of these indexes often relies on multivariate linear regression. However, Lai et al. proposed the use of ordered probability models [195] and polynomial logit models [196], and confirmed that both models demonstrated higher predictive accuracy than multivariate linear regression models.

Furthermore, the use of regression analysis to establish a connection between outdoor thermal perception and environmental and physiological variables may overlook potential interactions between these variables, which is referred to as a "black box model" [197,198]. Given that human outdoor thermal comfort is the result of a complex interplay of physiological, environmental, and psychological factors, this may lead to prediction errors [175]. Therefore, machine learning (ML), as a subset of artificial intelligence, can be employed to address complex nonlinear problems with a high dimensionality. ML demonstrates superior performance in identifying nonlinear and non-standard relationships between independent and dependent variables compared to regression methods [199]. Hence, this approach can be utilized for predicting outdoor thermal comfort in dynamic environments [200]. Consequently, empirical indicators should not only consider environmental variables but also take into account physiological variables. Higher precision regression analysis methods (ordered probability models, polynomial logit models) can be considered to derive expressions. Additionally, these methods can be extended for application in different climatic regions and compared with commonly used outdoor thermal comfort indicators (such as PET, UTCI, OUT_SET*) to validate the reliability of their predictive results. Machine learning, compared to regression methods, offers higher accuracy in predicting human thermal comfort and is currently more commonly used for assessing indoor thermal comfort, with fewer applications in outdoor thermal comfort prediction [200]. Therefore, utilizing techniques like machine learning for calculating outdoor thermal comfort holds promising prospects for future research.

4.1.4. The Summary of the Extension of the Theoretical Aspects of Outdoor Thermal Comfort Indicators

In theory, there are several areas where improvements are needed for outdoor thermal comfort indicators.

Firstly, linear indicators may need to be redefined. It might be incorrect to simply assume that indicators formed by the linear combination of variables are indeed linear indicators. Additionally, the applicability of linear indicators should be enhanced to accommodate different climate conditions, age groups, and gender groups.

Secondly, regarding mechanistic indicators, in the assessment of outdoor thermal comfort, PMV (predicted mean vote) demonstrates poor performance in predicting human outdoor thermal perception. It often tends to overestimate outdoor thermal perception. Therefore, PMV should not be used for evaluating outdoor thermal comfort. Furthermore, the development of mechanistic indicators should balance the accuracy of predicting outdoor thermal comfort outcomes and the convenience of calculation methods.

Thirdly, the construction of empirical indicators should take into account physiological factors such as clothing insulation and metabolic rate. Moreover, empirical indicators should be studied in various climatic regions. Additionally, empirical indicators should be compared with other commonly used outdoor thermal comfort indicators (such as PET, UTCI, OUT_SET*) to verify their reliability. Furthermore, empirical indicators should be combined with tools like machine learning to enhance their accuracy in predicting outdoor thermal comfort outcomes.

4.2. Expansion of the Application Sphere for Outdoor Thermal Comfort Indicators

In addition to the four aspects of research commonly addressed by researchers in China and other countries when studying the application of outdoor thermal comfort indicators—namely, quantifying outdoor human thermal perception, evaluating the outdoor thermal environment, measuring outdoor human thermal stress, and assessing the impact of outdoor environmental elements on outdoor thermal comfort—there is also a need in the research of outdoor thermal comfort indicators to analyze the application themes of future outdoor thermal comfort, the corresponding research methods under each theme, and the potential factors impacting evaluation results.

4.2.1. Monitoring and Controlling Regional Outdoor Thermal Comfort at the Temporal and Spatial Scales

Firstly, research on the application of outdoor thermal comfort indicators combines satellite remote sensing imagery and urban climate monitoring data to investigate regional outdoor thermal comfort at different spatiotemporal scales. For instance, Zhang, Yang et al. conducted a study in Chenggong District, Kunming, Yunnan, evaluating summer discomfort indexes for different time periods [106]. Cao, Qian et al. utilized a high-precision local climate zone (LCZ) map of downtown Wuhan to simulate 2 m heat indexes (HI) [201]. Geletic, Jan et al. employed the MUKLIMO-3 urban climate model and urban climate network measurements, using Humidex to assess spatiotemporal outdoor thermal comfort in Brno, Czech Republic [202]. It is noteworthy that Geletic et al. argue that Humidex incorporates simple influencing factors and is easy to obtain. Therefore, this indicator may be suitable for long-term outdoor environmental observation at an urban scale [203–205]. However, in the absence of detailed micro-scale meteorological data, commonly used indicators such as PET [206] and UTCI [207] have significant potential for evaluating outdoor thermal environmental conditions at an urban scale. Furthermore, although remote sensing data can capture large-scale surface temperatures, it is challenging to obtain air temperatures that directly impact the assessment of outdoor thermal comfort. Additionally, most studies on regional outdoor thermal comfort focus on tasks like identifying outdoor thermal environmental conditions at an urban scale [68,208], assessing variations in regional outdoor thermal comfort over time [209], analyzing outdoor thermal comfort under extreme climatic conditions [210], and predicting outdoor thermal comfort at a regional scale [211,212]. There has been relatively less exploration of the proposed driving factors of outdoor thermal comfort at an urban scale, understanding the magnitude of influence between these factors, and uncovering the underlying patterns that govern how these factors impact urban thermal comfort. However, such studies would necessitate long-term observations of land surface temperatures at an urban scale. Therefore, proposing the driving factors of outdoor thermal comfort at an urban scale, understanding the magnitude of their influence, and elucidating the underlying principles of how these factors affect urban thermal comfort may be a prospective research direction in the future of urban-scale outdoor thermal comfort studies [213].

4.2.2. Multi-Factor Coupling Effects on Outdoor Thermal Comfort

Secondly, research on the application of outdoor thermal comfort indicators also explores the impact of multi-factor coupling on outdoor thermal comfort. For example, the combination of environmental parameters and clothing index affects outdoor thermal comfort [108], and the perception of the acoustic-thermal environment impacts outdoor thermal comfort [214,215].

It is worth noting that when obtaining field-measured environmental parameters and subjective perceptions of individuals, it is necessary to establish methods for assessing outdoor thermal comfort. Firstly, it is important to consider the research objectives when selecting measurement times. Measurements should cover typical climate conditions in both summer and winter [9]. Typically, clear days are chosen for measurements to avoid interference from factors like overcast skies, rain, or snow [216]. The research location should be clearly specified, whether it is a park [143], square [217], street [218], residential area [219], campus [220], etc. Next, on-site measurements need to be conducted, involving equipment monitoring and questionnaire surveys. The measurement equipment should meet the requirements of ISO 7726 (1998) [221], and the range and precision of the measurement equipment should be comprehensively listed. Air temperature, relative humidity, wind speed and direction, radiation, and ground surface temperature are five common types of microclimate variables [17,221,222]. Additionally, wind speed and average radiation temperature exhibit rapid variations across different times and locations [223]. Therefore, the measurement methods and accuracy requirements for wind speed and average radiation temperature are particularly stringent.

As for mean radiant temperature, there are two methods to calculate mean radiant temperature. The first method involves using the integral radiation measurement to calculate it [224]. While this method provides accurate results, the equipment is expensive and has a response time of 10 min, which exceeds the time for questionnaire completion. Therefore, this method is rarely used to obtain mean radiant temperature [225]. The second method calculates mean radiant temperature using the globe temperature method. This method is simple to operate, and the equipment is affordable; however, the response time of the standard globe (D = 150 mm) is relatively slow [226]. Therefore, in on-site measurements, smaller globes with diameters of 38 mm or 50 mm are often used to quickly obtain data [227]. However, research by d'Ambrosio Alfano et al. indicates that smaller spheres tend to underestimate the heat convection coefficient. In situations with low wind speeds and higher radiation intensity, this can lead to a significant underestimation of globe temperature, resulting in a lower calculated mean radiant temperature [228,229]. Therefore, non-standard spheres should not be used for measuring globe temperature under conditions of low wind speed and high radiation [172].

As for wind speed, it is best to conduct three-dimensional measurements (not only at horizontal levels but also at vertical heights). Therefore, if low wind speeds are expected, cup or vane anemometers may provide inaccurate results, as they might erroneously record wind speeds below the measurement threshold as 0 [223]. Additionally, instruments should have fast response times and high measurement accuracy, and should be positioned at the center of a person's mass (at 0.6 m when seated and 1.1 m when standing). However, Johansson et al. argue that wind speed at 1.1 m height is determined by the wind profile power law. If atmospheric stability is not neutral, or if there is air turbulence, it may lead to inaccurate measurements [225].

The questionnaire typically includes individual information (such as age, gender, height, weight, clothing type, activity level) as well as thermal sensation, thermal comfort, and thermal preference. The design of questionnaires can be referenced from ASHRAE Standard 55-2020 [17] or from questionnaires used in related outdoor thermal comfort studies [230]. Among the outdoor thermal comfort studies, there are two types of sampling methods for participants: cross-sectional surveys and longitudinal surveys. Cross-sectional surveys allow researchers to quickly gather a large amount of data to understand the thermal sensations, behavior activities, and adaptation behaviors of the surveyed individuals. Therefore, this method is adopted by most researchers [231]. However, cross-sectional surveys can only collect data at specific times and cannot study outdoor thermal comfort in dynamic environments. Some studies use longitudinal surveys to control individual parameters of respondents (such as age, gender, thermal experience), enabling the study of outdoor thermal comfort conditions for specific age groups, genders, and thermal experiences. Due to the smaller sample size in longitudinal surveys [41], errors in the case of participant misreporting can lead to inaccuracies in the modified thermal sensation vote (MTSV), potentially resulting in errors in the modified outdoor thermal sensation scale [225].

Additionally, the calculation of sample size is an easily overlooked but important detail. In reality, sample size needs to be estimated considering factors such as the total population size, acceptable confidence level, margin of error, and response distribution [12]. Sharma et al. emphasize this in the context of data collection for outdoor thermal comfort [12]. Most studies use random sampling methods [232,233]. Sample size calculations can refer to the tables provided by Krejcie and Morgan [234]. Selecting an overly large sample size can lead to a significant workload for the survey [235], while selecting a too small sample can introduce substantial errors in the results of outdoor thermal comfort investigations [236]. Therefore, for cross-sectional surveys, an acceptable sample size ranges from 400 to 500 individuals [225].

Outdoor thermal comfort is impacted not only by physical factors such as sound, light, heat, and air quality, but also by physiological factors like age, gender, weight, and skin color [237]. For example, most research results indicate that older individuals tend to have lower thermal sensitivity compared to younger ones [238–241]. Therefore, it is necessary to conduct studies on the combined effects of various physical factors on outdoor thermal comfort for different age groups. Karyono found that individuals with a higher body mass index (BMI) tend to have a lower neutral temperature compared to those with normal weight [242]. Numerous studies also confirm that under the same indoor conditions and level of exercise, obese boys tend to feel warmer compared to non-obese boys [243–245]. Hence, it is important to study the impact of various physical factors on outdoor thermal comfort for different weight categories. Moreover, exploring the impact of these physical factors on emotional perception in humans could be a potential area of future research [246,247].

4.2.3. Human Health Assessment and Prediction Based on Outdoor Thermal Comfort

Furthermore, outdoor thermal comfort is also being applied in the assessment and prediction of human health. For instance, studies on the application of outdoor thermal comfort indicators combined with AT [248,249] and UTCI [250] have been conducted to evaluate and predict heat-related mortality. Although many researchers believe that climate change will lead to an increase in the occurrence of extreme weather events [251], and consequently impact human health, numerous studies indicate a strong relationship between environmental variables, particularly temperature, and mortality rates [252,253]. Therefore, outdoor thermal comfort indicators, as composite indexes considering both environmental and physiological variables, play a crucial role in assessing the impact of outdoor heat stress on human health [254]. However, many studies have relied on indicators like AT, which consider only environmental variables, to assess the link between climate change and outdoor human health [255]. Comprehensive indexes that take into account both environmental and physiological variables, such as PET [256] and UTCI [257], are less frequently used in studies evaluating the impact of outdoor heat stress on mortality rates.

Additionally, outdoor thermal comfort indicators are more commonly used to assess the incidence of weather-related diseases, such as respiratory and cardiovascular diseases [258]. However, there is a lack of research specifically focusing on the relationship between outdoor thermal comfort and human health for specific groups, such as women, the elderly, and children. In terms of gender, Follos et al. found that women are more susceptible to the effects of extreme high temperatures compared to men [259]. Regarding age, studies have indicated that the elderly have poorer adaptation to changes in thermal environments, particularly during cold spells [260] or heatwaves [261]. Additionally, children are more vulnerable to the impact of extreme climate conditions outdoors compared to adults [262]. For people with disabilities, individuals with physical impairments may have different heat adaptation responses under extreme climate conditions compared to those without disabilities. However, research in this area may involve ethical considerations, which is why there is relatively fewer studies on this topic. For instance, Webb et al.'s research showed that the percentage of multiple sclerosis patients dissatisfied with indoor thermal environments was significantly higher than Fanger's predictions, indicating that individuals with multiple sclerosis may be more heat-sensitive when compared to the healthy subjects [263].

Furthermore, the impact of outdoor thermal comfort on mental health should not be overlooked. For example, research has indicated that climate change can lead to adverse effects on mental health, including mild stress, anxiety, insomnia [264], and even depression, post-traumatic stress disorder, and suicidal thoughts [265]. However, the precise connections between climate change and mental health outcomes are still not clearly established. This includes questions about how to quantify human psychological activities, how to measure the impact of climate change on human psychological activities, how to define deviations from normal states in extreme climate events, and how to establish direct causal relationships [266].

The impact of outdoor thermal comfort on human health extends beyond physiological stress and mental well-being of specific populations. It also provides support for urban design and policy interventions. Therefore, some studies have visualized the spatial distribution of outdoor heat stress-related mortality, providing a basis for subsequent interventions in areas with high risk rates [267]. This represents a promising research direction within the realm of outdoor thermal comfort and its impact on human health.

4.2.4. Utilizing Computational Algorithms to Calculate Outdoor Thermal Comfort

Finally, outdoor thermal comfort is also assessed in conjunction with computer algorithms. For example, Bajsanski et al. utilize automatic algorithms with UTCI to assess and improve outdoor thermal comfort under non-steady-state conditions in urban areas [268]; Zhang et al. employ machine learning algorithms with UTCI to evaluate the outdoor thermal environment in older neighborhoods [269]; Lai et al. use a genetic algorithm with UTCI as the outdoor thermal evaluation index, determining the shape, size, and placement of buildings in the early stages of design to reduce overall thermal stress in outdoor spaces [270]. Machine learning (ML) demonstrates stronger performance in identifying nonlinear and non-standard relationships between independent and dependent variables. Therefore, ML has found widespread application in research related to human thermal comfort and building energy conservation. It is worth noting that ML models are mostly used for predicting human thermal comfort in indoor environments. There are fewer applications for predicting human thermal comfort in outdoor environments, possibly due to the complexity and variability of outdoor thermal conditions [271]. Therefore, the precise prediction of outdoor thermal comfort using ML models is a potential future research direction.

Moreover, models based on the concepts of machine learning and big data may yield varying levels of accuracy in their computed results due to different algorithms. According to research collected by Lai et al. on machine learning and thermal comfort, the main models used are: naive Bayes, K-nearest neighbor, decision tree, support vector machine, and random forest, all of which are considered high-precision models [175]. However, the usage conditions of different models may vary, ultimately affecting the predictive accuracy of outdoor thermal comfort. For instance, white-box models (naive Bayes, K-nearest neighbor, and decision tree) link environmental parameters with human thermal comfort to generate an expression. Therefore, white-box models can be interpreted. However, due to the complexity of factors impacting human thermal comfort and the subjective nature of comfort levels, quantification can be challenging. Unlike white-box models that rely on feature selection, black-box models (support vector machine, artificial neural network, random forest) can automatically learn inherent couplings between different features [272]. Therefore, black-box models can address complex problems that are hard to explain. However, when the boundary conditions set by black-box models change, they need to be retrained since the model is no longer valid [273]. Therefore, in future research, it is necessary to further identify the predictive performance of various ML models under different conditions to determine the applicable conditions and parameter setting ranges for the models [274].

Furthermore, machine learning can be utilized to develop thermal comfort indicators for different races, ages, and activity states. For instance, Zhou established a thermal regulation model tailored for Chinese individuals and also devised a thermal sensation model that takes into consideration individual differences and thermal psychological characteristics [275]. Both models were employed to predict thermal sensation votes (TSV) and skin temperature under non-uniform conditions. As the assessment of human thermal sensation lacks validation of physiological parameters (skin temperature, blood pressure, electrocardiogram) [175], Zomorodian et al. suggest that using minimally invasive novel lightweight sensors to collect physiological parameters may be a promising area of future research [274]. Therefore, acquiring potential influencing parameters poses a challenge to the predictive accuracy of ML models for outdoor thermal comfort.

4.2.5. The Summary of the Expansion of the Application Sphere for Outdoor Thermal Comfort Indicators

In future studies on outdoor thermal comfort application research, both in China and other countries, attention may be concentrated on four main areas. First, monitoring and controlling regional outdoor thermal comfort at the temporal and spatial scales. Second, multi-factor coupling effects on outdoor thermal comfort. Third, human health assessment and prediction based on outdoor thermal comfort. Fourth, utilizing computational algorithms to calculate outdoor thermal comfort.

In relation to the first point, potential research directions for urban-scale outdoor thermal comfort include investigating the driving factors, their degree of impact, and the underlying principles through which these factors affect outdoor thermal comfort.

For the second point, it is crucial to ensure data quality during the data collection process for outdoor thermal comfort studies. Moreover, studying how various physical factors affect different demographic groups, such as gender, age, weight, and skin color, is a future research direction.

Regarding the third point, potential research areas include the application of physiological equivalent temperature (PET) and the universal thermal climate index (UTCI) to assess the impact of outdoor thermal stress on mortality rates. Furthermore, future studies may explore the effects of outdoor thermal comfort on the health of different population groups, such as the elderly, children, and individuals with disabilities. Additionally, examining the impact of outdoor thermal comfort on the psychological well-being of the population and visualizing the mortality rates associated with climate-related diseases in geographical areas represent possible avenues for research.

For the fourth point, using machine learning to predict outdoor thermal comfort, evaluating the applicable conditions and parameter ranges of various computational models within machine learning, and acquiring parameters with potential impact on outdoor thermal comfort to enhance machine learning computational models are three potential research directions for the future.

5. Conclusions

This study, based on the results retrieved from the Web of Science database, reviews the application of outdoor thermal comfort indicators in China and other countries. It summarizes the differences in research themes on outdoor thermal comfort indicators between the two sides, outlines the research trends in the application of outdoor thermal comfort indicators, and discusses potential directions for the development of outdoor thermal comfort indicators in both theoretical and practical aspects. The following are the main conclusions drawn from this study:

(1) In the research of outdoor thermal comfort indicators, other countries have developed earlier than China, with a concentration in developed regions such as Europe, America, and Asia. The average citation count per paper is higher than in China, and there is closer academic cooperation compared to China.
(2) The top five indicators most commonly used in both China and other countries are: PET (including mPET), UTCI, PMV, SET* (including OUT_SET*), and THI (including DI). Additionally, compared to other countries, China tends to use PET and UTCI at a higher frequency.
(3) For mechanistic indicators, researchers in China and other countries share similar research themes. However, when it comes to linear indicators and empirical indicators, researchers in other countries tend to have a wider range of research topics in these categories compared to their Chinese counterparts.
(4) In the assessment of human thermal health, China tends to focus on individual behavior and psychological factors, while other countries are more concerned with measuring outdoor human heat stress. Regarding the optimization of outdoor thermal environments, China emphasizes proposing strategies for improving outdoor thermal conditions, whereas other countries tend to evaluate the condition of outdoor

thermal environments. The aforementioned research trends reflect a shared aspiration among researchers to address issues related to improving outdoor environments and promoting physical and mental health. This will become increasingly crucial in the future sustainable development of cities.

(5) Regarding the theoretical aspects of outdoor thermal comfort indicators, firstly, for linear indicators, they need to be redefined and their applicability across different climate conditions, age groups, and gender groups should be enhanced. Secondly, for mechanistic indicators, there is a need to develop an indicator that provides accurate predictions, has a simple calculation method, and can be applied in various climate conditions. Additionally, PMV is considered unsuitable for evaluating outdoor thermal comfort. Thirdly, for empirical indicators, research should be conducted in different climatic regions, and its reliability should be compared with indicators like PET, UTCI, and OUT_SET*. Furthermore, these indicators should be combined with tools like machine learning to enhance the predictive capability of outdoor thermal comfort. These are potential directions for the theoretical development of outdoor thermal comfort indicators. Future research can focus on developing outdoor thermal comfort indicators that are highly accurate in prediction and have simple calculation methods. Combining these indicators with machine learning algorithms can enhance the speed and precision of outdoor thermal comfort assessment. This will enable researchers to provide more accurate assessments of outdoor thermal comfort for different populations (based on factors such as age, gender, and thermal experience) in various climate conditions. Ultimately, this will contribute to the development of sustainable solutions for urban planning.

(6) Potential future applications of outdoor thermal comfort indicators include: "monitoring and controlling regional outdoor thermal comfort at the temporal and spatial scales", "multi-factors coupling effects on outdoor thermal comfort", "human health assessment and prediction based on outdoor thermal comfort", and "utilizing computational algorithms to calculate outdoor thermal comfort". With the continuous advancement of the four aforementioned research directions, sustainable outdoor environmental planning and design will have more reference points.

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