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Review

A Review of Thermal Comfort Evaluation and Improvement in Urban Outdoor Spaces

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Abstract: Urban outdoor space is an important activity place for residents, and its thermal environment directly affects residents' quality of life and physical and mental health. Due to global climate change and the acceleration of urbanization, the outdoor thermal comfort of urban residents has seriously declined, causing more and more scholars to pay attention to this problem and to carry out research. This paper summarizes the development history and evaluation principles of outdoor thermal comfort evaluation indices and sorts out the methods for achieving outdoor thermal comfort. This paper reviews the effects of urban climate, local microclimate, physiological, psychological, social, and cultural factors on outdoor thermal comfort. In addition, strategies for improving thermal comfort in urban outdoor spaces are discussed from the aspects of urban geometry, vegetation, surface materials, and water bodies. Finally, the existing problems and development directions of current urban outdoor space thermal comfort studies are pointed out. This review paper can provide a reference for the scientific planning and construction of urban outdoor spaces to improve people's thermal comfort.

Keywords: outdoor thermal comfort; microclimate; urban outdoor spaces; mitigation strategies

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1. Introduction

According to the latest United Nations Human Settlements Programme report, the total global urban population in 2022 was 4.46 billion, accounting for 57.5% of the world's total population [1]. Urban outdoor space is an important space for urban residents and a key factor in sustainable urban development. It provides physical, environmental, social, and economic benefits to citizens [2]. For example, Chiesura collected 467 questionnaires in urban parks in Amsterdam, the Netherlands, and confirmed that urban nature fulfills many social functions and psychological needs of citizens, which makes urban nature a valuable municipal resource [3]. Comfortable urban outdoor spaces provide high-quality places for residents to engage with the outdoors [4]. In urban planning and architectural design, creating a comfortable thermal environment in outdoor spaces is significant in improving the attractiveness and vitality of urban outdoor spaces [5]. For example, the number of visitors to open outdoor spaces in summer and winter depends on changes in the thermal index. During the hot season, the higher the outdoor temperature, the fewer the visitors [6–8].

However, due to global climate change and the acceleration of urbanization, urban outdoor spaces face severe thermal environment problems, such as global warming, urban-heat-island effect, heat stress, and reduced thermal comfort [9–12]. These problems not only undermine the health and well-being of urban residents but also increase energy consumption and greenhouse gas emissions [13–15]. For example, in 1995, an estimated 619 extra deaths occurred during a five-day heatwave in England and Wales [16]. In Paris, studies on the impact of the urban heat island (UHI) on regional atmospheric pollution showed that the spatial distribution of pollutants was significantly influenced by the intensity of the urban heat island in each region [17]. To alleviate heat stress, many people choose to stay in air-conditioned rooms instead of enjoying the natural sun and wind [18]. This leads to a sedentary lifestyle, which further affects their physical and mental health as well as the building's energy consumption. Therefore, improving the thermal environment quality of urban outdoor spaces has become an important issue.

To improve the above problems and improve thermal comfort, people need to evaluate and improve the thermal comfort of urban outdoor spaces to provide guidance and suggestions for urban planning and architectural design. Over the past two decades, scholars worldwide have conducted a lot of research on the thermal comfort of urban outdoor spaces under various climate conditions. Through field measurement and a questionnaire survey, they have analyzed the relationship between the outdoor thermal environment and human thermal comfort [19–27]. Researchers have proposed many design strategies to improve the thermal comfort of outdoor spaces. For example, some studies have found that changing urban geometry can enhance thermal comfort [20,28,29]. In addition, rational arrangement of vegetation, road pavements, and water bodies can effectively improve the quality of the outdoor thermal environment [30–37]. However, these design strategies have different effects on improving urban outdoor thermal comfort in different climate regions, at different times, and in different spaces. Therefore, it is necessary to conduct an up-to-date review of research on thermal comfort in urban outdoor spaces to understand the current state of research and to propose current problems as well as future research directions.

Our search of the literature identified previous review articles: Potchter et al. reviewed the most used human thermal indices, and studied the relationship between indices and climatic conditions [38]; Coccolo et al. reviewed existing outdoor human comfort and thermal stress modeling tools, and demonstrated their applicability [39]; Lai et al. reviewed benchmarks, data collection methods, and models for outdoor thermal comfort [40]. Chen and Ng reviewed studies on outdoor thermal comfort behavior [41]; Kumar and Sharma quantified the importance, procedures and future scope of outdoor thermal environments [42]; Li and Liu reviewed the current status of outdoor thermal comfort studies in China [43]. Taleghani reviewed the impact of vegetation and highly reflective materials on human thermal comfort in urban open spaces [44]; Jamei et al. reviewed studies on pedestrian-level urban greening and geometric design in improving urban thermal comfort [45]; Lai reviewed the mechanisms and cooling effects of changing urban geometry, planting vegetation, using cool surfaces, and incorporating water bodies [46]. However, existing studies reviewed from one aspect and ignored other aspects. This paper aims to provide a comprehensive and systematic review of the key and latest research results on the evaluation methods, influencing factors, and improvement strategies of thermal comfort in urban outdoor spaces. The review results can provide a scientific basis for urban outdoor space design and a reference for further research on urban outdoor space thermal comfort. Compared with other published studies in this field, this paper is more comprehensive, more systematic, and original.

The structure of this review is shown in Figure 1. First, the research background on outdoor thermal comfort is introduced. Secondly, the urban thermal comfort evaluation method is presented, including the definition of outdoor thermal comfort, the development trend of outdoor thermal comfort evaluation indices, and the methods of obtaining outdoor thermal comfort. Then, the influencing factors of outdoor thermal comfort are summarized, including urban climate conditions, microclimate conditions, physiological factors, psychological factors, and social and cultural factors. Next, strategies for adjusting thermal comfort in urban outdoor spaces are summarized, including adjusting outdoor space forms, vegetation, surface materials, and water bodies, and the interactions between each strategy are discussed. Finally, the limitations and challenges of thermal comfort studies in urban outdoor spaces are pointed out, as well as future study directions.

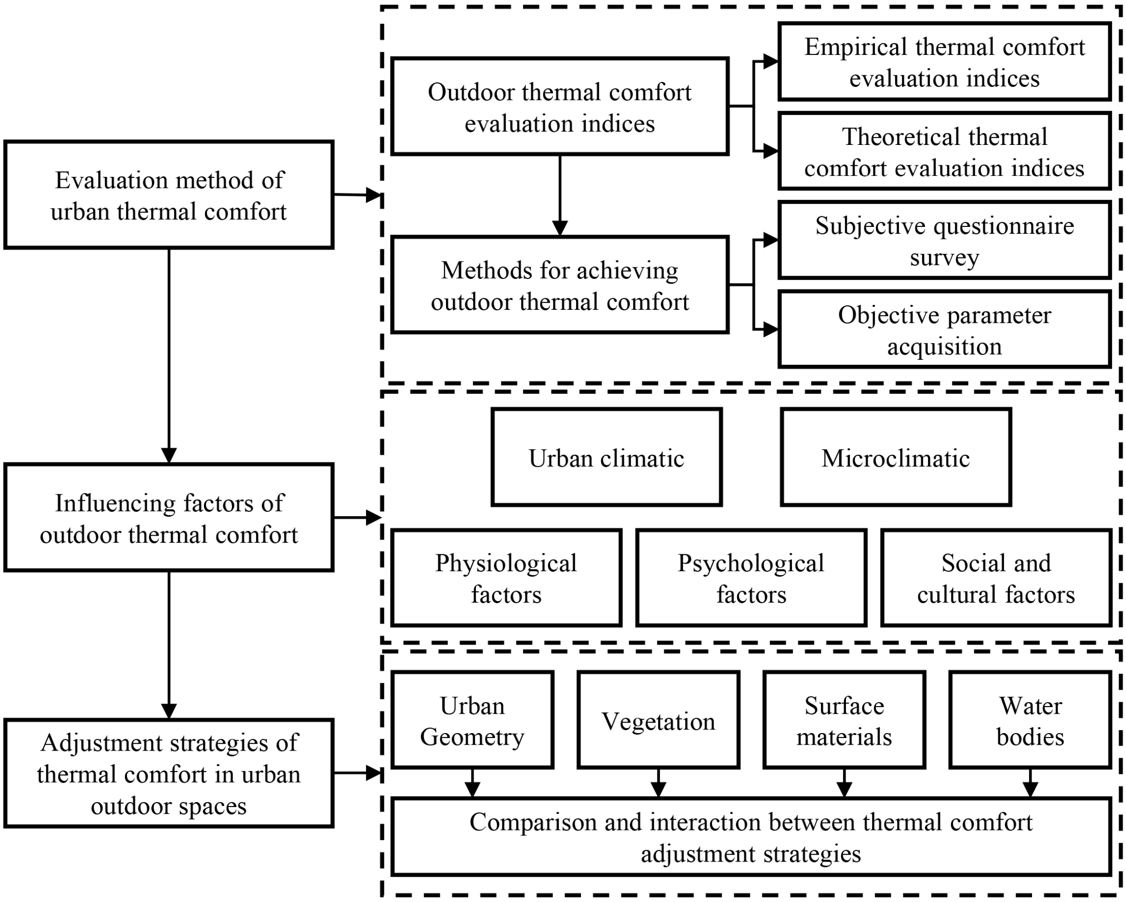

Figure 1. Structure of this review.

2. Review Methods

A systematic review of existing articles was conducted using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework [47]. In the Web of Science and Scopus databases, "outdoor thermal comfort", "outdoor thermal comfort indices", "questionnaire", "measurement", and "mitigation" were selected as keywords. All documents from 1 January 2000 to 1 January 2023 were searched. The specific steps are as shown in the Figure 2. First, two search engines, Web of Science and Scopus, were selected to obtain 281 articles from the Web of Science core library and 351 articles from Scopus, for a total of 632 articles. Secondly, the papers in the two databases were screened and aligned, and duplicate papers were removed for further analysis, resulting in 374 papers. Article types were then filtered to limit the search to research and review articles, resulting in a total of 274 articles. Afterwards, titles/abstracts/methods were screened to eliminate papers irrelevant to the research topic. Finally, 232 high-quality relevant articles were obtained.

The distribution of years related to this topic is shown in Figure 3. It can be inferred that study on outdoor thermal comfort has increased over the past decade. The distribution of study types of papers related to this topic is shown in Figure 4. It can be seen that experimental papers account for the most, accounting for 51%, followed by numerical papers. In addition, there are many studies that combine experimental and numerical study types.

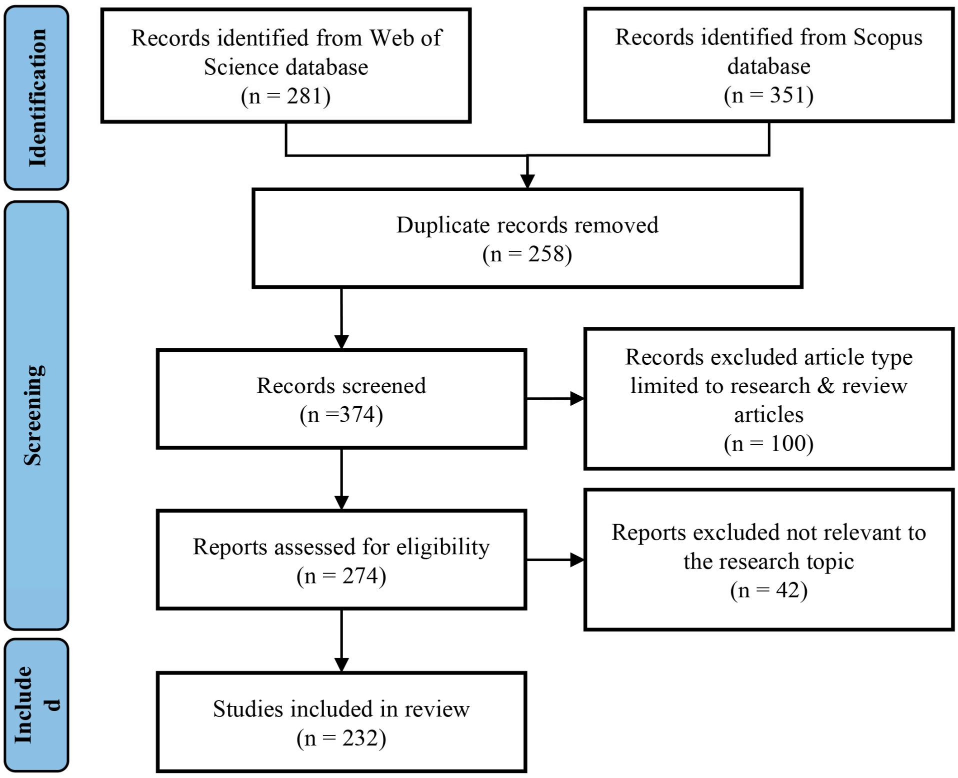

Figure 2. Flow diagram of the literature selection and review process.

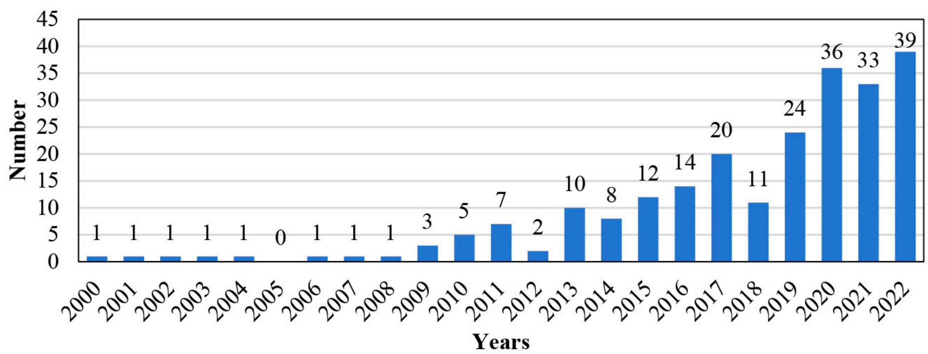

Figure 3. Year-wise distribution of papers related to this topic.

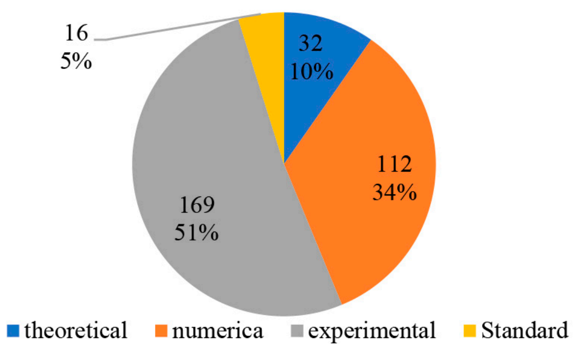

Figure 4. Distribution of study types among papers related to this topic.

3. Evaluation Method of Urban Thermal Comfort

The thermal comfort of urban outdoor space is of great significance to urban planning, architectural design, landscape design, transportation, tourism, and other fields. In order to evaluate and improve outdoor thermal comfort, some scientific methods and indices need to be used. This paper introduces the definition of outdoor thermal comfort comprehensively and systematically summarizes the outdoor thermal comfort evaluation indices and methods for obtaining outdoor thermal comfort.

3.1. Definition of Outdoor Thermal Comfort

Thermal comfort refers to the human body's degree of satisfaction or indifference to the thermal environment. Different institutions and scholars have different definitions of thermal comfort. The most commonly used definition is proposed by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), which defines thermal comfort as the condition of mind that expresses satisfaction with the thermal environment [48]. The glossary of terms for thermal physiology defined thermal comfort as subjective indifference to the thermal environment [49]. Gagge et al. mentioned that "Comfort" is a recognizable state of feeling but possesses no identifiable sense organ like the basic five senses [50].

Outdoor thermal comfort is a complex concept affected by many factors, such as environment, individual, and psychology [40]. Among them, environmental factors include solar radiation, wind speed, air temperature, humidity, etc., which directly affect the thermal balance and thermal sensation of the human body [51]. Individual factors include age, gender, physiological activities, etc., which affect the thermal regulation ability and thermal adaptability of the human body [52]. Psychological factors include experience, expectations, activity purposes, etc., which affect the human body's thermal satisfaction and thermal preference [53]. Therefore, when studying outdoor thermal comfort, the role and interrelationship of these factors need to be comprehensively considered.

3.2. Outdoor Thermal Comfort Evaluation Indices

Since thermal comfort is affected by multiple factors, any single factor cannot accurately describe the human body's subjective experience of the thermal environment. The thermal comfort index combines multiple thermal environment parameters and human body parameters into a single index to describe thermal comfort more accurately and conveniently.

Since ASHRAE proposed the first thermal comfort index, Effective Temperature (ET), in 1923 [54], people have studied thermal comfort for a hundred years. Currently, about 165 different thermal comfort indices have been developed [42], which can be divided into two categories: empirical thermal comfort evaluation indices and theoretical thermal comfort evaluation indices. Table 1 summarizes the commonly used thermal comfort evaluation indices and their applicable environment and climates. Table 2 summarizes the factors that need to be considered for the above thermal comfort evaluation indices.

Table 1. Classification and application scope of commonly used thermal comfort evaluation indices.

Classification		Index	Year	Author	Applicable Environment	Applicable Climate
Empirical indices	Hot empirical indices	Heat Stress Index (HSI)	1955	Belding and Hatch [55]	Indoor and outdoor hot environment	Hot climate
		Wet Bulb Globe Temperature Index (WBGT)	1957	Yaglou and Minard [56]	Indoor and outdoor hot environment	All climate
		Discomfort Index (DI)	1959	National Weather Service researcher Thom [57]	Outdoor hot environment	Hot climate
		Heat Index (HI)	1990	National Weather Service [58]	Outdoor hot environment	All climate

Table 1. *Cont.*

Classification		Index	Year	Author	Applicable Environment	Applicable Climate
	Cold empirical indices	Wind Chill Index (WCI)	1945	Paul Siple et al. [59]	Outdoor cold environment	All climate
		Wind Chill Equivalent Temperatures (WCT)	1963	Eagan [60]	Outdoor cold environment	All climate
		New Wind Chill Equivalent Temperature (NWCT)	2001	United States and Canadian meteorological services [61]	Outdoor cold environment	All climate
Theoretical indices	Steady-state indices	Effective Temperature (ET)	1923	Houghton and Yaglou [62]	Indoor hot environment	Hot climate
		New Effective Temperature (ET*)	1971	Gagge et al. [63]	Indoor hot environment	Hot climate
		New Standard Effective Temperature (SET*)	1972	Gagge et al. [64]	Indoor hot environment	Hot climate
		Outdoor Standard Effective Temperature (OUT_SET*)	2000	J.Pickup and R.de Dear [65]	Outdoor hot environment	Mild to hot climate
		Predicted Mean Vote (PMV)	1970	Fanger [66]	Indoor environment	All climate
		Physiologically Equivalent Temperature (PET)	1987	Mayer and Höppe [67]	Outdoor environment	All climate
	Dynamic indices	Universal Thermal Climate Index (UTCI)	2002	Commission 6 of the International Society of Biometeorology [68]	Outdoor environment	All climate

Table 2. Parameters related to commonly used thermal comfort evaluation indices.

Index	Air Temperature	Relative Humidity	Wind Speed	Average Radiant Temperature	Skin Moisture	Core Temperature	Clothing Thermal Resistance	Human Metabolic Rate
HSI	√			√				√
WBGT	√	√	√	√				
DI	√	√						
HI	√	√						
WCI	√		√					
WCT	√		√					
NWCT	√	√	√			√		
ET	√	√	√					
ET*	√	√	√		√	√		
SET*	√	√	√		√	√	√	√
OUT_SET*	√	√	√	√	√	√	√	√
PMV	√	√	√	√			√	√
PET	√	√	√	√	√	√	√	√
UTCI	√	√	√	√	√	√	√	√

3.2.1. Empirical Thermal Comfort Evaluation Indices

Empirical thermal comfort evaluation indices were mostly formed in the early stages of thermal comfort studies. It establishes indices of heat and cold risks based on the relationship between the physical environment and human thermal sensation. It is usually limited to estimating the combined effects of air temperature, air humidity, and air velocity on sedentary individuals [69]. Empirical indices are mainly categorized into hot empirical indices and cold empirical indices, which are used to evaluate thermal comfort in high- and low-temperature environments, respectively. The advantages of empirical indices are that they are simple to calculate and easy to understand. However, there are also some shortcomings, such as ignoring the decisive role of human physiology, activities, clothing, and other personal data (height, weight, age, gender), and their application is limited by factors such as geography and climate [70]. Therefore, when using empirical indices, it is necessary to combine other types of indices, such as dynamic indices and adaptive indices etc., to improve the accuracy and applicability of evaluation.

Hot Empirical Indices

Hot empirical indices establish an index for judging subjective feelings in hotter environments by studying the relationship between physical environment factors and thermal sensation. Commonly used hot empirical indices include Heat Stress Index (HSI), Wet Bulb Globe Temperature Index (WBGT), Discomfort Index (DI), Heat Index (HI), etc.

In 1955, Belding and Hatch developed the Heat Stress Index (HSI), which represents the degree of heat exposure of the human body when operating in a high-temperature environment and can be used to evaluate human adaptability and safety in a high-temperature environment [55]. In 1957, Yaglou and Minard proposed the Wet Bulb Globe Temperature (WBGT) to prevent thermal casualties in military training [56]. WBGT is still widely used in various industries to assess thermal safety in the workplace. In 1959, Thom, a researcher at the National Weather Service, proposed the Discomfort Index (DI), which represents the level of human comfort under high-temperature conditions by combining dry bulb temperature and wet bulb temperature [57]. Later, to avoid the negative impact of the name on other industries, such as tourism, the name was changed to Temperature–Humidity Index (THI). In 1979, Steadman proposed Apparent Temperature (AT). This model studies the impact of different humidity on human thermal sensation, taking into account physiological factors, clothing conditions, and amount of exercise [71]. The model was later renamed Heat Index (HI) after its transformation by the National Weather Service to simplify the calculation [58].

Cold Empirical Indices

Cold empirical indices establish an index for judging cold risk by studying the relationship between physical environment factors and thermal sensation. In cold climate conditions, the main factors affecting human thermal comfort are wind speed and air temperature. Commonly used cold empirical indices are Wind Chill Index (WCI), Wind Chill Equivalent Temperatures (WCT), New Wind Chill Equivalent Temperature (NWCT), etc.

In 1945, Paul Siple et al. exposed snowmelt water in a cylindrical container to the environment in the Antarctic region to calculate the cooling capacity, which is the Wind Chill Index (WCI), which represents the cooling rate of the skin surface when the skin temperature is 33 °C [59]. WCI is used in the wilderness and non-wilderness weather reports to warn people of possible frostbite hazards caused by cold weather [72]. WCI and WCT derived from 1963 have been widely used to represent the heat loss of skin exposed to the environment due to changes in wind speed. Still, researchers have also criticized it because it was unreliable in some respects [60]. After subsequent improvements and modifications by scientists, the New Wind Chill Equivalent Temperature (NWCT) of the United States and Canadian Meteorological Services in 2001 used an updated biophysical model that can predict the risk of frostbite [61].

3.2.2. Theoretical Thermal Comfort Evaluation Indices

As people understand the mechanism of thermal comfort more and more deeply, they not only pay attention to the physical environment but also comprehensively consider individual physiological and psychological factors and dynamic balances. Therefore, theoretical indices began to appear, which are numerical models established based on the human body heat-balance equation and comprehensively considering environmental and human body parameters [70]. Due to the different methods and models adopted by various research institutions, theoretical indices show a diversified development trend. According to the scope of application of thermal comfort evaluation models, they can be divided into steady-state indices and dynamic indices [41]. Theoretical indices are conducive to objectively evaluating human thermal comfort in complex environments and produce more scientific evaluation results.

Steady-State Thermal Comfort Evaluation Indices

The steady-state model considers that human thermal comfort arises from the steady-state heat transfer between the human body and the environment [70]. That is, the human body and the environment are in contact with each other for a long time and reach thermal equilibrium [73]. The energy exchange between the human body and the surrounding environment can be expressed using the thermal energy balance Equation (1):

$$M + W + Q^* + Q_H + Q_L + Q_{SW} + Q_{RE} = S \quad (1)$$

where M is the metabolic rate (i.e., internal energy production from food oxidation), W; W is the output value of physical work, W; Q^* is the total radiation of the body, W; Q_H is the convective heat flux (sensible heat), W; Q_L is the latent heat flux caused by water vapor diffusion, W; Q_{SW} is the latent heat flux caused by sweat evaporation, W; Q_{RE} is the respiratory heat flux (the sum of the heat used to heat and moisturize the respiratory air), W; and S is the heat storage for heating (positive value) or cooling (negative value) of the body, W. The difference between the existing various steady-state thermal comfort evaluation indicators is only a supplement to the equation and individual-related parameters.

In 1923, Houghton and Yaglou conducted experiments. They defined the temperature at which subjects in standard clothing felt the same thermal sensation when walking in two environments with different temperatures and humidity as the Effective Temperature (ET). However, this index can only be equivalent to air temperature and humidity factors [62]. In 1971, Gagge et al. improved ET in his study, and introduced the concept of skin moisture, and named it New Effective Temperature (ET*) so that this index can consider the evaporative heat dissipation of the human body [63]. In 1972, Gagge et al. proposed the New Standard Effective Temperature (SET*) at a seminar. This index comprehensively considers the two factors of activity level and clothing thermal resistance based on ET*, making the index applicable to different physiological conditions and dressing situations. Still, the formula calculation is relatively complex [64]. The above indices are commonly used indoors, and there are errors in studying outdoor thermal comfort. The main differences between indoor and outdoor environments are solar radiation and infrared radiation. In 2000, J.Pickup and R.de Dear introduced Outdoor Mean Radiant Temperature (OUT_MRT) and established the Outdoor Standard Effective Temperature (OUT_SET*) to make the SET* model suitable for outdoor thermal comfort [65]. By comparing actual measured values with predicted values, the OUT_MRT model can describe the outdoor radiation environment and calculate the total outdoor radiation absorbed by the human body.

From the 1960s to the 1970s, Danish scholar Fanger proposed a classic thermal comfort model, Predicted Mean Vote (PMV), based on the human body's heat-balance equation, using a seven-point scale to predict the average thermal sensation vote of most people. The PMV model is widely used to evaluate indoor thermal comfort [66]. At the same time, he also proposed the Predicted Percentage of Dissatisfied (PPD), which is used to express the proportion of people who feel too hot or too cold [74]. Since the PMV model is mainly suitable for traditional air-conditioning environments and does not consider non-stationary and dynamic environments, large errors exist when it is used in outdoor environments [75].

In 1987, German applied meteorologists, Mayer and Höppe proposed Physiologically Equivalent Temperature (PET) based on the Munich Energy-balance Model for Individuals (MEMI) steady-state two-node model, which is still widely used now [67]. PET can be understood as the actual outdoor climate being transferred to an equivalent effective indoor environment in which the same expected air temperature can be obtained. In 2007, Matzarakis et al. proposed the RayMan model to facilitate the calculation of PET and improved the model in 2010 [76].

Dynamic Thermal Comfort Evaluation Indices

The steady-state model believes that the heat exchange between the human body and the thermal environment is in a steady state. It must meet the two assumptions of stable thermal environment conditions and long-term contact with the human body and the environment. It is limited to situations where people stay outdoors for a long time. However, in the actual outdoor thermal environment, the heat load of the human body is constantly changing [24]. Therefore, a dynamic model was established, considering that the human body can also produce thermal comfort when the heat storage rate is non-zero. Commission 6 of the International Society of Biometeorology initiated the Universal Thermal Climate Index (UTCI), which aims to assess outdoor thermal conditions in major areas of human biometeorology [68]. UTCI is calculated based on the equivalent temperature obtained by conducting more than 100,000 thermal physiological simulations using the multi-node dynamic thermal physiology UTCI-Fiala model, which represents the equal environmental temperature at which the subject obtains the same physiological response as the real environment in the reference environment [77]. UTCI can accurately evaluate outdoor thermal comfort in different climates and is widely applicable to all regions worldwide, but the model structure is complex.

3.3. Methods for Achieving Outdoor Thermal Comfort

The main methods to achieve outdoor thermal comfort include a questionnaire survey and thermal environment parameter acquisition. Information about subjective psychological adaptation can be obtained through a questionnaire survey, and physical information about the thermal environment can be obtained through thermal environment parameters. Researchers usually use a combination of questionnaire surveys and thermal environment parameter acquisition to analyze the thermal sensation and comfort of the human body [43].

3.3.1. Subjective Questionnaire Survey

A questionnaire survey is used to collect the subjective feelings and satisfaction of the human body in the outdoor environment through questionnaires or field interviews and then derive indices such as outdoor thermal comfort range or neutral temperature based on statistical analysis, which is usually used to verify and calibrate theoretically predicted values. The advantage of this method is that it can directly reflect the subjective feelings of the human body. Still, the disadvantage is that it is affected by individual differences, psychological factors, questionnaire design, and other factors, making it difficult to form a unified standard.

The content of the questionnaire survey consists of two parts. The first part serves to collect basic information about the human body, including survey location, survey time, respondent gender, age, weight, height, activity and activity level, clothing thermal resistance, metabolic rate, etc. [42]. The second part serves to collect the interviewees' subjective perceptions about the thermal environment they were in at that time. It mainly includes the Thermal Comfort Vote (TCV), Thermal Sensation Vote (TSV), and Thermal Preference Vote (TPV). The specific scales are shown in Table 3. TCV refers to people's evaluation of satisfaction with the thermal environment. The 7-point scale originally established by Bedford is widely used [78]. In addition, the 4-point scale was established by Winslow and Herrington, and the 5-point scale was used by the International Standard Organization (ISO)10551 [79,80]. TSV refers to people's subjective feelings of "cold" and "hot" in the thermal environment. The ASHRAE's 7-point scale is widely used [81], and since then a 9-point scale and an 11-point scale have been introduced [48,82]. TPV refers to people's willingness to change the thermal environment. McIntyre's 3-point scale is more popular than ISO10551′s 7-point scale due to its practicality [80,83].

Table 3. Commonly used subjective perception scales.

Subjective Perception	Standards	Scale	Scale Details
Thermal comfort vote (TCV)	Bedford, 1936 [78]	7-point scale	Cold (−3), Cool (−2), Comfortably cool (−1), Comfortable (0), Comfortably warm (1), Warm (2), Hot (3)
	Winslow and Herrington, 1949 [79]	4-point scale	Comfortable (0), Slightly uncomfortable (1), Uncomfortable (2), Very uncomfortable (3)
	ISO10551, 1995 [80]	5-point scale	Comfortable (0), Slightly uncomfortable (1), Uncomfortable (2), Very uncomfortable (3), Extremely uncomfortable (4)
Thermal sensation vote (TSV)	ASHRAE, 1966 [81]	7-point scale	Cold (−3), Cool (−2), Slightly Cool (−1), Neutral (0), Slightly warm (1), Warm (2), Hot (3)
	ASHRAE, 1992 [48]	9-point scale	Very cold (−4), Cold (−3), Cool (−2), Slightly cool (−1), Neutral (0), Slightly warm (1), Warm (2), Hot (3), Very hot (4)
	ASHRAE, 2004 [82]	11-point scale	Extremely cold (−5), Very cold (−4), Cold (−3), Cool (−2), Slightly cool (−1), Neutral (0), Slightly Warm (1), Warm (2), Hot (3), Very hot (4), Extremely hot (5)
Thermal preference vote (TPV)	McIntyre, 1978 [83]	3-point scale	Cooler (−1), No change (0), Hotter (1)
	ISO10551, 1995 [11,80]	7-point scale	Colder (−3), Cooler (−2), Slightly cooler (−1), Neutral (0), Slightly warmer (1), Warmer (2), Hotter (3)

3.3.2. Objective Parameter Acquisition

Thermal environment parameters are obtained using field measurement, numerical simulations, and a combination of measurements and simulations [46,84].

In order to ensure the authenticity of the research, real weather data are usually needed to calculate the heat index or calibrate the simulated meteorological data [43]. Field measurements usually use instruments to manually measure air temperature, relative humidity, wind speed, and black ball temperature at selected test points or read selected parameters from weather stations to obtain microclimate data. There are also options for mobile measurements, thermal remote sensing, or scale models. For example, Busato et al. installed instruments on cars in Padua that followed several different predetermined paths through different areas of the urban space: urban, suburban, and rural, measuring the main thermal and humidity variables (air temperature, relative humidity, global solar radiation), and studied the urban-heat-island effect [85]. Remote sensing observations of urban heat islands using satellite and aircraft platforms can obtain large-area surface temperature, but they cannot directly reflect air temperature and other parameters [86]. Scale models can simulate urban environments outdoors or indoors. For example, Imam Syafii et al. used the Comprehensive Outdoor Scale Model (COSMO) designed at a scale of 1:5 to quantitatively demonstrate the spatial and temporal effects of evaporative cooling of a typical water body in the form of a pond in an urban canyon, evaluating the studied impact of various water body configurations (in the form of artificial ponds) on the urban thermal environment, with special emphasis on pedestrian comfort [87].

When experimental control is required, numerical simulation of the urban outdoor environment can be used. Commonly used models include the energy balance model (EBM) or computational fluid dynamics (CFD) [88]. EBM calculates energy balance on limited nodes through the law of energy conservation and has high computational efficiency. Still, it cannot provide coupling information of the velocity and temperature fields [88]. CFD can perform simulations with clearly coupled velocity fields, temperature fields, and other fields and can analyze an urban climate on a small scale. For example, Hassen et al. used a CFD model that combined meteorological data and urban terrain data to simulate the urban environment of the city of Hail (Saudi Arabia) [89]. But, it requires high-resolution input data and computing resources, which can be simulated through ENVI-met software (https://www.envi-met.com/) [90]. Numerical simulations can be performed at different scales, from city scale to building scale, but need to be verified with field measurement to improve credibility and accuracy.

The combination of measurement and simulation can compensate for the lack of measurement. For example, a method for predicting outdoor thermal comfort using measured thermal parameters and simulated wind speed was adopted. CFD was used to simulate wind-speed distribution, radiant temperature, air temperature, and humidity were monitored on-site to evaluate the potential impact on pedestrian thermal comfort [85].

4. Influencing Factors of Outdoor Thermal Comfort

Existing studies have shown that outdoor thermal comfort is affected by many direct or indirect factors, some classified as geography and seasonality, climatic conditions such as temperature, thermal radiation, wind and humidity, individual physiological differences, social and cultural factors, and personal behavioral habits, etc. [40,51,91]. This paper analyzes the existing research literature and elaborates on it from five aspects: urban climate conditions, local microclimate conditions, physiological factors, psychological factors, and social and cultural factors.

4.1. Urban Climatic

Urban climate conditions are the most important and direct factor affecting the local microclimate and thermal comfort of outdoor spaces and are also the premise of related research [92,93]. According to the Köppen–Geiger climate classification, this paper combs through the relevant literature. It explains the research status of outdoor thermal comfort in different climate zones, from tropical climate zones, arid climate zones, temperate climate zones, continental climate zones, and polar climate zones [94]. The number of studies conducted in different climate regions is shown in Figure 5. Most studies have been undertaken in subtropical climate zones, and no research has been found in polar climate zones.

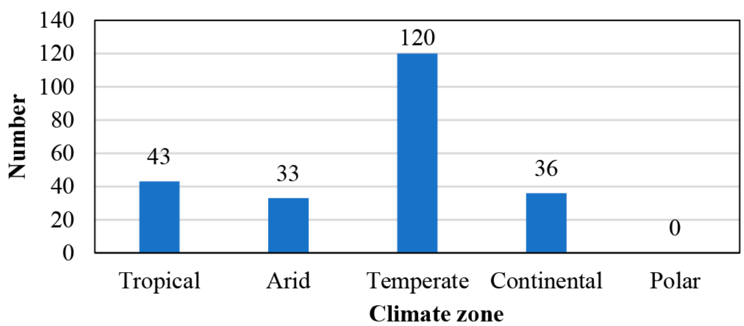

Figure 5. The number of papers describing thermal comfort in each climate zone.

Tropical climate zones are mainly in South Asia, Central America, and Africa, and they are eager to improve the thermal comfort of outdoor spaces by summarizing the laws of climate change [95–97]. The thermal comfort range in tropical areas is generally higher than in temperate and continental regions. In Tanzania Dar es Salaam, Ndetto and Matzarakis found that the thermal comfort range is 23–31 °C of PET, which is much higher than the thermal comfort range in temperate climates [98]. In the thermal sensation assessment of Brazil, de Arêa Leão Borges et al. found that the thermal comfort zone lies between 21.5 and 28.5 °C, with both thresholds higher than those observed in studies conducted in subtropical, Mediterranean, and continental temperate climates [99]. In hot climates, people have a high tolerance to climatic conditions, but a neutral temperature cannot be considered a comfortable temperature because people may be satisfied with a lower temperature [100]. Yang et al. found that in tropical climates, people under outdoor conditions may be more tolerant of heat stress than people under indoor conditions, which is consistent with the findings of Hwang and Lin [101–103].

Arid climate zones account for one-third of the Earth's land surface but have received little attention in outdoor thermal comfort studies [38,104]. The climate conditions in arid areas are harsh, with extremely hot summers, severe cold winters, and extreme heat pressure changes during the day in all seasons [104–106]. Exposure of the human body to extreme heat loads can cause health hazards, which are exacerbated by urbanization [107,108]. Since the large difference in heat between summer and winter in arid climate zones, assessing human thermal sensation requires measurements in all seasons to determine comfort ranges [109]. Cohen et al. modified the PET full scale for arid climates. The modified Neutral PET ranges between 17 °C and 26 °C, showing adaptation to low rather than high temperatures, which is wider than in Mediterranean and hot, humid climates [104]. Yahia and Johansson found that the neutral temperature of both PET and OUT_SET* in Damascus, Syria, was found to be lower in summer than in winter, and determined the upper limit of summer comfort and the lower limit of winter comfort of PET and OUT_SET* in hot and dry Damascus [109]. In Cairo, Egypt, Elnabawi et al. showed that the thermal comfort range of PET is 23–32 °C, with the preferred temperature being 29 °C PET in summer and 24.5 °C PET in winter, which were higher than those of the temperate climates and European scale, confirming the existence of thermal adaptation [110]. In addition, Ruiz and Correa developed a new model in Argentina: "Thermal comfort Index for cities of Arid Zones (IZA)" to predict the thermal comfort conditions of people adapted to this arid climate "oasis city". The prediction ability of IZA is 73% [111].

Temperate climate zones include European countries along the Mediterranean Sea, parts of the United States, and southern China. They generally have relatively developed economies and attach great importance to the environmental problems and climate disasters caused by urban climate change, so they are the most relevant to research. This climate zone has higher thermal comfort ranges and neutral temperatures than continental zones. In Taichung, Taiwan, Lin found that respondents' thermal comfort range was 21.3–28.5 °C PET, which was significantly higher than studies conducted in Central and Western Europe [6]. Similarly, in Tel Aviv, Israel, Cohen et al. showed that the "neutral" TSV range for the Mediterranean climate was between 20 and 25 °C PET, which is higher than in temperate climates and lower than in hot and humid climates [112]. In recent years, some studies have focused on finding the most suitable thermal comfort model for assessing the local thermal environment, and there are differences in the predictive performance of commonly used thermal comfort indices for temperate climates [18,113–115]. For example, Fang et al. conducted a comprehensive comparison of commonly used outdoor thermal comfort indices. For hot outdoor environments, the relationship between these indices and the mean thermal sensation vote (MTSV) has not yet been determined, and the ranges of heat stress categories and PMV need to be modified for hot outdoor environments [116]. In Nagoya, Japan, Watanabe found that compared with UTCI and OUT_SET*, the universal effective temperature (ETU) model can provide a more detailed understanding of the various parameters affecting thermal comfort in the outdoor environment [117]. Shading structures such as buildings and pergolas with plants can reduce ETU values considerably during summer in humid subtropical regions. Salata et al. developed the Mediterranean Outdoor Comfort Index (MOCI) to assess thermal comfort in the Mediterranean region [118]. Subsequently, Golasi et al. studied the performance of this index and showed that the prediction accuracy of MOCI was 35.5%, which was better than the results of PMV (32.3%) or PET (29.6%) [119].

For continental climate zones due to the drastic climate changes throughout the year and the difficulty of transformation it has not been extensively studied. Researchers mainly focus on thermal adaptation and influencing factors [120,121]. In Tianjin, China, Lai et al.

found that the neutral PET range was 11–24 °C, which was lower than the range in Europe and Taiwan, and the residents of Tianjin were more adapted to cold environments [122]. Leng et al. in Harbin, China, experimented with residential, public open spaces and found that the 90% thermally acceptable PET range was more than 10.2 °C for this period in the winter cities, which was much lower than the threshold in temperate and subtropical zones [123]. In Umea, Sweden, Yang et al. found that Umea natives, who were exposed to a wider range of climates, were more adapted to the subarctic climate than non-natives [124]. A study by Xi et al. in Harbin, China, showed that both locals and tourists responded to outdoor environments with thermal insulation in clothing during summer and winter, with tourists wearing more dresses than locals in winter [125]. The activity levels of tourists are not affected by the outdoor thermal environment, whereas the activity levels of locals are affected by the outdoor environment in summer. Hou et al. studied in Harbin, China, Central Street, and showed that compared with other nodes, concave squares were more likely to create a good microclimate environment in commercial streets in cold cities [126].

4.2. Microclimate

The microclimate of urban outdoor space is the focus of thermal comfort studies [42,46]. A large number of studies have shown that air temperature, humidity, wind speed, and solar radiation are the physical parameters most commonly used to describe an urban microclimate and play a major role in outdoor thermal comfort [27,46].

Air temperature is the most important factor affecting outdoor thermal comfort. It directly determines the convective heat transfer between the human body and the surrounding air and also indirectly affects the radiation, evaporation, and respiration heat transfer [27]. Many studies have found that air temperature has the highest correlation with human thermal sensation, and it is also the most prevalent microclimate parameter [122,127–129]. Tsitoura et al. found in Crete that temperature and solar radiation are the most critical determinants of comfort voting [129]. However, the air temperature is difficult to adjust in the outdoor space, and passive strategies are generally needed to reduce the air temperature.

Humidity is usually the least important factor affecting outdoor thermal comfort. It mainly affects the evaporative heat transfer and respiration heat transfer of the human body. In most cases, the effect of humidity on outdoor thermal comfort is negligible [27,122,128,130]. However, in areas with high temperatures and high humidity, humidity can increase the discomfort of the human body because high humidity can hinder the sweat and heat dissipation of the human body [5,131].

Wind speed is a complex factor that affects outdoor thermal comfort. It can not only increase the convective heat transfer of the human body but also bring psychological comfort. The effect of wind speed on outdoor thermal comfort is related to factors such as the magnitude, direction, and variability of wind speed, as well as the position, posture, and activity of the human body. For example, Hnaien et al. studied the wind comfort of pedestrians in urban areas and confirmed that weather conditions (wind speed and wind direction) and building layout are key parameters for comfort [132]. Most studies have found that wind speed has less effect on outdoor thermal comfort than radiation [102,127,133], while other studies have found that wind speed has a greater impact on outdoor thermal comfort than radiation [133–135]. This may be related to the climate characteristics of different regions. Generally speaking, wind speed will be perceived as stronger in low-temperature climates, possibly due to greater convective heat loss at lower air temperatures [136–138]. Furthermore, Oliveira and Andrade in Lisbon found that stroke was the most strongly perceived variable, usually perceived negatively [139].

Solar radiation is the most complex of the four basic parameters and mainly affects the radiation heat transfer of the human body. Solar radiation includes three forms: direct, scattered, and reflected. Direct radiation has the greatest impact on the human body. Solar radiation in outdoor spaces is usually described by mean radiant temperature (T_{mrt}), which is a parameter that combines long-wave and short-wave radiation. The mean radiant temperature is related to the surface temperature of the surrounding environment, so solid surfaces such as building facades and floors play an important role in outdoor thermal comfort. Most studies have found that the effect of radiation is greater than that of wind [103,140–142].

4.3. Physiological Factors

Due to individual differences, people may have different thermal sensations even in the same outdoor thermal environment. This paper will analyze the relevant results of studies in different groups of people in terms of gender, age, weight, and skin color.

4.3.1. Gender

After collecting relevant information through the questionnaire survey, the researchers divided the data according to gender and compared the difference in outdoor thermal comfort between males and females. Most studies (Schellen et al. [143], Villadiego and Velay-Dabat [100], etc.) have shown that females are more sensitive to outdoor thermal environments than males. Still, some studies found that there is no significant difference between males and females in their feelings and preference for outdoor thermal environments.

In terms of cold sensation, females are more susceptible to cold and prefer cooler environments than males. Amindeldar et al. confirmed that females were more sensitive to cold air temperature changes [144]. In Cuenca, Galindo and Hermida found that females had a higher intolerance to lower temperatures [145]. Oliveira and Andrade found that females showed a stronger negative reaction to high wind speed than males [139]. Rutty and Scott found that female beach users preferred the cooling sensation more than males [146]. In Wuhan, China, Huang et al. found that females preferred cooler environments than males [147].

In terms of heat sensation, females are more sensitive to high temperatures than males and prefer warm environments. Karjalainen found that females preferred higher room temperatures than males and felt uncomfortably cold and uncomfortably hot more often than males [148]. Lindner-Cendrowska and Błażejczyk reached a similar conclusion [149]. Lan et al. found that females were more sensitive to temperature and less sensitive to humidity than males, and females preferred neutral or slightly warmer thermal sensations [150]. Indraganti and Rao found that females expressed slightly higher thermal sensation and preferred warmer environments [151]. Tung et al. found that females in Taiwan were less tolerant to hot conditions and strongly protected themselves from sunlight [152]. Cohen et al. found that women were more sensitive to high temperatures and more tolerant to low temperatures in winter [104]. However, Jin et al. found that females had a lower tolerance to thermal environments than males under different environmental conditions [153].

However, another group of researchers found no significant difference in the perception of the thermal environment between males and females. Karyono found that the difference in neutral temperature and comfort range between male and female subjects was very small and statistically insignificant at the 5% level [154]. Yin et al. found that males and females perceived the thermal environment similarly [141]. Shooshtarian and Ridley found that gender had a negligible effect on thermal perception [155]. Kruger and Drach found that the gender effect in modulating the effects of thermal conditions was not significant and not statistically significant [156]. Both Lai et al. [157] and Ali and Patnaik [158] found that there was no significant difference in outdoor thermal sensation between subjects of different genders.

4.3.2. Age

Similar to gender, through data analysis of different ages, the difference in perception of the thermal environment among people of different age groups has been compared. Some studies have found that age had a certain effect on sensation and preference for outdoor thermal environments. Kruger and Drach found that age effects might be a concern in climate-sensitive urban design [156], and Amindeldar et al. found that younger people were more sensitive to cold [144]. However, another part of the studies found that age had no significant effect on sensation and preference for outdoor thermal environments. Karyono found that the difference in neutral temperature between subjects under and over 40 years was not statistically significant at the 5% level [154]. Indraganti and Rao observed a significant but poor correlation between age and thermal sensation and overall comfort [151].

Some studies have found that older adults were less sensitive to temperature changes. János et al. found that older adults were less sensitive to temperature changes and were less fond of changes in the thermal environment [159]. Andrade et al. [160], Krüger and Rossi [134], Pantavou et al. [161], Lindner-Cendrowska and Błażejczyk [149], and others also reached similar conclusions. Furthermore, Rutty and Scott found that older beachgoers (over 55 years old) preferred warmth more than younger beachgoers (18 to 25 years old) [146]. In Wuhan, China, Huang et al. found that older adults had a lower tolerance to cold stress compared with younger groups [147]. Yung et al. found that factors affecting thermal perception in older adults were different in winter and summer in Hong Kong [162].

For studies on children, children's behavioral activities and metabolism are different from adults, so the effect of the thermal environment on children may be different from other populations [163]. Mors et al. found that the PMV model did not accurately predict children's thermal sensations and that children preferred lower temperatures than predicted by these methods [164]. Teli et al. found that children were more sensitive to higher temperatures than adults [165,166]. Nam et al. found that children preferred lower temperatures than adults [167]. Lai et al. found that children had the highest thermal sensation because they were most active; although older adults wore more clothes, their thermal sensation was the lowest [122]. Vanos et al. found that children were more susceptible to heat stress and high temperatures than adults [168,169]. Cheng and Brown found that children's thermal acceptance range was different from adults and provided an effective children's energy budget model COMFA-kid (CK) to predict children's thermal comfort [170].

4.3.3. Weight and Skin Color

There are relatively few studies on the effect of body weight and skin color on outdoor thermal comfort, and the results vary widely. Most studies have shown that individuals with higher Body Mass Index (BMI) have lower neutral and comfort temperature and sweat more than those with lower BMI [154,171,172]. However, Karyono found that there was a slight difference in neutral temperature and comfort range between 'thin' and 'normal' subjects. The difference was not statistically significant at the 5% level [154]. Tuomaala et al. found that BMI had a small effect on thermal sensation data, and an increase in BMI slightly reduced the thermal sensation index used in prediction [173]. Kruger and Drach found that normal-weight individuals had the highest thermal sensation, followed by overweight individuals, and obese individuals had the lowest thermal sensation [156].

Despite the evidence found on the relationship between skin color and thermoregulation through the varying absorptivity of solar radiation of different skin colors [174,175], there has been no convincing explanation of how skin color affected thermal perception in humans [176]. Galindo and Hermida found that skin color had a low effect on thermal sensation [145]. However, Shooshtarian and Ridley demonstrated that skin color, along with other factors, affected thermal sensation in outdoor environments, observing higher sensitivity in dark-skinned subjects than in light-skinned subjects [155]. Kruger and Drach found that absolute thermal sensation was consistently higher in dark-skinned groups than in light-skinned groups [156].

4.4. Psychological Factors

Psychological factors were first proposed in a study of thermal comfort in urban open spaces by Nikolopoulou and Steemers. They found that the psychological factors of respondents led to huge differences in the results of questionnaire data and theoretical prediction data [53]. Different psychological factors have different effects on outdoor thermal comfort. Some psychological factors may enhance or weaken people's perception of environmental temperature, and some psychological factors may change people's expectations or preferences for environmental temperature. For example, people in cold areas were more adaptable to low-temperature environments, and residents in tropical cities had a higher tolerance for high temperatures [52,177]. In summer, people might expect or prefer lower temperatures, while the opposite is true in winter [128,178]. When people were in a good mood, they might feel warmer, and when people were in a low mood, they might feel colder [145].

In order to accurately evaluate outdoor thermal comfort, the influence of psychological factors needs to be considered. A common method is to establish a regression model of objective data and subjective thermal sensation voting results through microclimate measurements and questionnaire surveys to obtain a regional thermal sensation voting model and thermal comfort threshold range [177]. However, this method is based on surveyed group data. It cannot represent the outdoor thermal comfort situation of the whole region, requiring studies from multiple spaces and groups in different areas. Paying attention to the effect of psychological adaptation is helpful in explaining the difference in outdoor thermal comfort evaluation results under different climate backgrounds.

4.5. Social and Cultural Factors

Social and cultural factors are mainly analyzed from the social background and cultural differences of different regions, including regional clothing, life concepts, national character, religious beliefs, etc. [40,179]. These factors have an important effect on people's daily lives and cognition, thereby affecting their perception and adaptation to the outdoor thermal environment. Different social and cultural backgrounds may lead to people's different preferences and behaviors in terms of sunlight, clothing, activity selection, etc., which in turn affect people's sensitivity and tolerance to climate factors [152]. In addition, socioeconomic level and academic background may also affect people's subjective evaluation of the outdoor thermal environment. Generally speaking, people with better economic conditions and higher education would be more sensitive [52]. In order to evaluate and predict the outdoor thermal comfort level of people in different regions, it is necessary to consider the effect of social and cultural factors and establish a reasonable and complete classification system and evaluation indices. There have been some studies that have explored the impact of social and cultural factors on outdoor thermal comfort and proposed some evaluation models and methods [145,155,180,181]. However, sufficient consensus has not yet been formed, and further in-depth analysis and refinement is needed.

5. Adjustment Strategies of Thermal Comfort in Urban Outdoor Spaces

5.1. Urban Geometry

Urban open spaces come in different shapes and sizes, which affect thermal comfort by changing radiation and convective heat exchange within urban open areas. Urban outdoor space geometry is mainly quantified through factors such as sky view factor (SVF), height-to-width ratio (H/W), and street orientation.

SVF is a dimensionless number that represents the amount of unobstructed sky seen from a given point [182]. For irregular and complex spaces such as squares, parks, and residential communities, shading by buildings and vegetation reduces the SVF, resulting in reduced solar radiation, which is conducive to thermal comfort in hot climates. Lower SVF usually results in a lower daytime temperature and higher nighttime temperature [183–185]. The cold-island effect during the daytime causes air and average radiation temperatures to decrease because solar radiation is difficult to penetrate. The heat-island effect at night is hindered by long-wave radiation and turbulent heat transfer, causing the air temperature to rise. Low SVF values prevent long-wave radiation in urban canyons from dissipating, causing the urban surface to cool slowly [186]. In Athens, Greece, it was found that low

SVF and dense green coverage resulted in an 8.7 °C decrease in PET levels [28]. A study by Lin et al. in Taiwan was shown in Figure 6 (adapted from [187]). High SVF locations were uncomfortable in summer, low SVF locations were uncomfortable in winter, and the median shading level (SVF = 0.129) contributed to the longest thermal comfort period in an entire year [187]. In terms of wind speed, SVF can indicate the airflow rate driven by thermal buoyancy under windless conditions, and a 10% increase in SVF will result in an 8% increase in wind speed at pedestrian level [188].

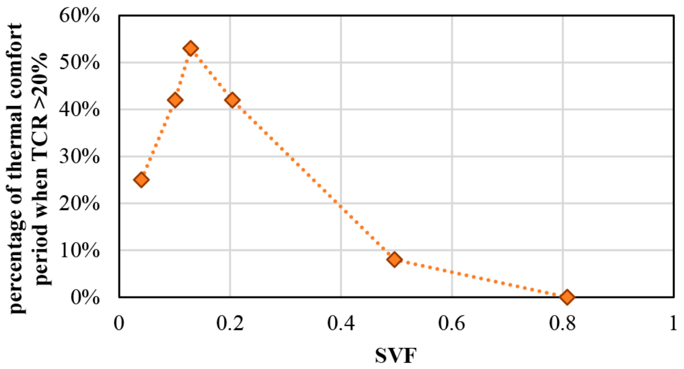

Figure 6. Correlation of SVF and percentage of thermal comfort period when thermal comfort ratio (TCR) > 20%.

H/W is the ratio of building height to street width and is an important factor indicating the openness of urban canyons. Generally speaking, the larger the H/W, the more compact the space, and the smaller the H/W, the more open the area. H/W affects solar radiation, long-wave radiation, and airflow velocity in urban canyons, which in turn affects air temperature and average radiation temperature. Streets with high H/W provide more shade, which can reduce solar radiation and improve thermal comfort in summer but is detrimental to thermal comfort in winter [45]. Ahmed found that in the hot and humid summer in Dhaka, Bangladesh, the maximum temperature decreased as H/W increased [189]. Wider spacing between buildings may lead to increased daytime temperature [190,191]. A comparison of the effects on air temperature in urban canyons at three different H/W (H/W = 3, 2.1, 1.7) in the densely populated urban area of Athens, Greece, showed that with the decrease of H/W, the median, maximum, and minimum cooling rates at night increased significantly [192]. However, the combination of tall buildings and narrow streets can negatively affect outdoor thermal comfort in summer by lowering high air temperatures and reducing airflow [193].

Solar radiation and wind speed in urban canyons are significantly affected by street orientation, which plays an important role in pedestrian thermal comfort [188,194]. In a study in Vancouver, Canada, researchers found that street orientation affected the state of thermal balance in urban areas [195]. Many studies have found that east–west streets have the worst thermal conditions, while north–south streets have better thermal conditions [70,191]. This is due to the fact that east–west streets are exposed to longer hours of sunlight during the summer than north–south streets. Furthermore, for low-rise buildings, a north–south orientation is recommended, but for high-rise buildings, there is no preferred orientation [196].

In summary, the SVF, H/W, and direction of urban outdoor space affect outdoor radiation, wind speed, and temperature, which in turn affect thermal comfort. In hot climates, reducing radiation and air temperature can improve thermal comfort, but at the same time, reducing wind speed can reduce thermal comfort. Through the evaluation of thermal comfort indices such as PET, researchers found that the PET value of compact spaces is lower than that of open spaces, indicating that the shading effect is greater than the wind effect [197,198]. Therefore, in summer, compact spaces have a better urban thermal environment than open spaces, but in winter, the situation is different. Although the compact urban form is beneficial to thermal comfort in summer, it is not conducive to thermal comfort in winter [45]. More solar radiation is needed in winter, and wide streets are more comfortable. When designing urban forms for outdoor thermal comfort, the balance between hot and cold seasons should be considered based on the regional climate characteristics.

5.2. Vegetation

Vegetation is one of the most important natural elements in a city. It can reduce air temperature and surface temperature through transpiration, shading, and changing wind speed, and increase air humidity and negative oxygen ion content, thereby improving the urban microclimate.

Tree shading has the most significant impact on the microclimate, which can effectively reduce the amount of solar radiation received by the ground and make the temperature lower than that in non-shaded areas. It is considered to be one of the key factors in reducing summer temperature and mitigating the urban-heat-island effect [199–201]. The shading effect of trees is related to the tree's coverage area, height, canopy shape, leaf characteristics, and types [11]. Many studies have found that trees have the effect of lowering air temperature and reducing cooling load in different regions and seasons [15,202–206]. In addition, although street trees can cool down and improve comfort, it is necessary to consider the characteristics of the tree and the street, pay attention to the shape and wind direction of the street, and select appropriate tree species and distribution methods.

The use of vegetation in the park has a great cooling effect. Some researchers have found that the average temperature of the park is significantly lower than the surrounding built-up areas, which can effectively reduce the heat-island effect [207–209]. The daytime temperature reduction of vegetation is attributed to evapotranspiration and shading, while the nighttime cooling effect is attributed to an increase in radiative cooling potential and a substantial decrease in convective heat released from stored energy during the day [210,211]. Feysia et al. measured the air temperature and humidity in 21 parks in Addis Ababa. They found that the types of plants, the normalized difference vegetation index (NDVI), and the size and shape of the parks were closely related to the cooling effect of the parks [212]. Chang et al. measured air temperature in and around 61 City parks in Taipei, and the results showed that larger parks were cooler than smaller parks at any time [207].

Vegetation is applied to the roof to form a green roof, which can reduce the roof surface temperature through reflection and evapotranspiration effects, thereby reducing the cooling load of the building [213]. Ouldboukhitine et al. built an experimental platform with a green roof on the campus of the University of La Rochelle in France and found that the maximum roof surface temperature could be reduced by 20 K in summer [214]. Santamouris found that the use of green roofs on a city scale reduced average ambient temperatures by 0.3 to 3 K [215]. Furthermore, the temperature effect of green roofs on pedestrian height depends on the height of the building. The use of green roofs on low-rise buildings may have a cooling impact on pedestrians [216]. Berardi's model tests in France found that when using green roofs on buildings with a height of about 10 m, the air temperature at the pedestrian level during the day would be reduced by 0.4 K [217]. However, when green roofs are used in middle- and high-rise buildings, their cooling effect on pedestrian height becomes insignificant [218]. Chen et al. simulated two areas in Tokyo, Japan, with average heights of 29 m and 68 m, respectively, and found that roof greening had almost no cooling effect at street level [219].

Vegetation is used on the facade to form vertical greening, which can effectively improve the indoor and outdoor thermal environment quality of buildings. Bianco et al. found that vertical greening reduced the outdoor surface temperature of walls by 23 K [220]. Tan et al. found in a vertical greening experiment that the T_{mrt} increased by 12.8 K after the green wall was removed [221]. Bartfelder and Köhler found that the cooling effect of green walls depended on the outdoor temperature. On cold days and hot days, the cooling effects of green walls were 0.4 °C and 5.8 °C respectively [222]. Wong et al. observed a temperature reduction of 3.33 °C at a distance of 0.15 m from the green wall, while almost no effect was felt at a distance of 0.60 m [223].

5.3. Surface Materials

The use of materials with high reflectivity on building facades, roofs, and road pavements can reflect a large amount of solar radiation, reduce surface temperature, improve urban climate, and alleviate urban heat islands [15,224].

When high-reflectivity materials are used in road pavements, the results measured by Chatzidimitriou and Yannas confirmed the inverse relationship between the hard pavement surface temperature and its reflectance value. That is, the high reflectivity surface appears cold and vice versa [225]. However, this also means that they increase the amount of short-wave radiation that is reflected in space, which may be greater than the reduction in long-wave radiation due to the cooler pavement surface. Taleghani and Berardi reduced the air temperature in Toronto by increasing the reflectivity of the square pavement, but the increase in T_{mrt} and PET by 10.53 °C and 4.7 °C, respectively, reduced the thermal comfort of the pedestrian layer [226]. Therefore, pavements with high reflectivity, such as light-colored materials, may actually reduce outdoor thermal comfort despite their cooler surface.

Reflective roofs and white roofs can reflect most of the solar short-wave radiation, reduce the heat absorption of the roof, save energy, extend the life of the roof, and improve thermal comfort [227–230]. Almeria, Spain, is a typical case of implementing white roofs (26,000 hectares), and the average ambient temperature in this city is 0.3 K lower than that in rural areas [231]. Santamouris found that for every 0.1 increase in roof reflectivity, the air temperature at a height of 2 m dropped by about 0.2 K [215]. Because convective cooling of air occurs at the roof surface, the impact of reflective roof cooling effects on pedestrian height may diminish as building height increases. However, reflective roofs may also cause increased radiant temperature above the roof, causing thermal discomfort. Taleghani et al. compared black roofs (albedo 0.37) and white roofs (albedo 0.91) and found that white roofs increased T_{mrt} by 2.9 K but decreased air temperature by 1.3 K [232]. Rosso et al. tested the effect of the combination of facade and pavement reflectivity in a historic urban canyon with an aspect ratio of 3.5. The simulation results showed that the lowest thermal stresses were found for the scheme with a high-reflectivity pavement and a low-reflectivity wall [233]. However, the reason for this result is unclear.

Although reflective materials can theoretically reduce the urban-heat-island effect, most studies are based on computer models, and the results are inconsistent [33,34,234,235]. Some studies have shown that reflective materials can significantly reduce air temperature [34,236,237], while others have found that the effect is small or negligible [238–242]. In addition, reflective materials also have different effects on the thermal comfort of occupants, depending on a variety of factors. It is necessary to test further the impact of reflective materials on the urban microclimate and thermal comfort through field measurement and a questionnaire survey.

5.4. Water Bodies

Water bodies have a cooling effect on the urban thermal environment due to their high heat capacity and evaporation. Water bodies can absorb more solar radiation than common building and pavement materials without significantly increasing their temperature, thereby acting as heat sinks in urban space. This leads to a reduction in long-wave radiation and temperature at the water surface, as demonstrated by measurement and simulation [243]. The cooling effect of a water body on air temperature depends on many factors, such as the area, shape, location, and surrounding environment of the water body [244]. However, water bodies also increase humidity in the air, which may reduce evaporative heat loss of the human body through sweat and affect thermal comfort. Therefore, the trade-off between reduced air temperature and increased humidity caused by water bodies should be quantified.

Water bodies have a limited effect on thermal comfort compared to vegetation and urban geometry because they do not block direct solar radiation. Water can improve thermal comfort by lowering air temperature and mean radiant temperature, but the effect varies with wind direction and distance from the water. Some studies have shown that the reduction of PET by water can reach about 1 to 2 K, and the best distance to the water edge for improving thermal comfort is 10~20 m [37,225,245].

5.5. Comparison and Interaction between Thermal Comfort Adjustment Strategies

In order to improve the thermal comfort of urban outdoor space as much as possible, some studies have compared the differences in the degree of different adjustment strategies and the rules of interaction between them [246].

Lai et al. compared the regulating effect of four strategies on outdoor thermal environment quality at noon or in the afternoon in summer, including changing geometry, increasing vegetation, using reflective surfaces, and combining water bodies, and summarized the maximum decreases in air temperature and PET for each strategy. It is found that the temperature reduction of different strategies was similar. However, in terms of PET reduction, changing the geometry had the greatest cooling effect (median reduction = 18.0 K), followed by increasing vegetation (median reduction = 13.0 K), and having a high reflectivity surface which will reduce outdoor thermal comfort [46]. Similarly, O'Malley et al. used ENVI-met to simulate the effectiveness of UHI mitigation strategies during the day, as shown in Figure 7 (adapted from [247]) and found that trees, shrubs, and grass (TSG) were the most effective strategies, followed by urban inland water bodies (UIWB), and finally the use of high-albedo materials (HAM) [247].

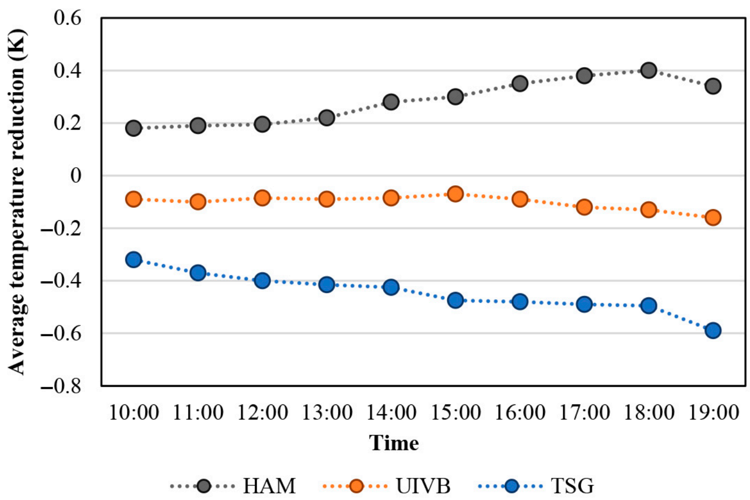

Figure 7. All UHI mitigation strategies compared to benchmark: average temperature reduction during the daytime.

Some studies have concluded that the use of plants and green spaces achieved better results in reducing mean radiant temperature and air temperature than surface material reflectance or urban geometry elements such as building height and road density [248]. For example, Salata et al. compared different microclimate strategies on the campus of the Sapienza University of Rome and found that the most beneficial option was to use highly reflective roofs and pavements, as well as urban vegetation [249]. If the site used only asphalt and removed all vegetation, conditions deteriorated. Martins et al. found that doubling the aspect ratio provided an average decrease of 1 °C in terms of PET, and the shading effect associated with the cooling effect of plant evapotranspiration allowed an average drop in PET of 7 °C [250]. The use of relatively high water fountains coupled with airflow also had a cooling effect. In addition, differences in site spatial form will also affect the impact of various thermal comfort adjustment strategies. For example, Ng et al. concluded in Hong Kong that when the building height in the site was low (20 m), the cooling effect of ground greening and roof greening on pedestrian height was higher than when the building height was high (40 m or 60 m) [218].

In addition, the same urban outdoor space design strategy will have different effects on thermal comfort under different climate conditions. The hotter and drier the climate, the greater the impact of vegetation on urban temperature [251]. For example, under the same configuration of green walls and green roofs, the calculated temperature reduction in Riyadh, Saudi Arabia, is over 11 K, while the value in Moscow, Russia, is less than 4 K. Therefore, comprehensive consideration of site geometry, plant, and water configuration, and building and pavement surface materials, depending on the geographic and climatic characteristics of the city is crucial for improving the outdoor thermal comfort of the residents [45].

6. Discussion

In this paper, the evaluation methods, influencing factors, and improvement strategies for the thermal comfort of urban outdoor space are comprehensively reviewed and summarized. However, there are still some limitations in the current research, and the future research can be deepened and expanded from the following aspects:

(1) Existing studies on the thermal comfort of urban outdoor space mostly focuses on the tropical climate zone, arid climate zone, temperate climate zone, and continental climate zone [42]. Still, there are few related studies on extreme climate conditions. Research on outdoor thermal comfort in extreme climate areas should be conducted further, such as on alpine areas, desert areas, polar areas, etc., to explore the thermal comfort and thermal adaptation mechanisms of people in these areas and provide guidance for outdoor space design in these areas. In addition, current studies mostly focus on the climate characteristics of a single typical season in a certain city and propose design strategies to improve outdoor thermal comfort [40]. Still, these design strategies may not be applicable in other seasons. Therefore, future research should focus on year-round climate change and global climate change and derive outdoor thermal comfort improvement strategies that can balance different seasonal climates and adapt to future climate changes.

(2) Thermal comfort indices in the current study are mostly generated based on population data in certain areas, e.g., MOCI was based on studies of Mediterranean populations [118]. The applicable areas are limited, e.g., in the Mendoza city, Argentina, the predictive capabilities of the six thermal comfort indices widely used internationally were all very low [111]. They still need to be corrected and verified in different areas to improve the accuracy of the model. Many factors affect thermal comfort, and researchers should give priority to factors with greater influence when developing or improving models. Develop and verify thermal comfort evaluation indices that are more suitable for different areas and climates, taking into account various factors such as human physiology [100,143,151,154,156,171,172], psychology [52,128,145,177,178], behavior [40,51,91], and culture [40,52,145,152,155,179–181]. This aims to improve the accuracy and universality of thermal comfort evaluation. A common thermal comfort evaluation model should be established in areas with the same climate conditions and cultural background so as to form a standardized and unified thermal comfort evaluation model.

(3) Although there are many urban outdoor space adjustment strategies to improve thermal comfort, these adjustment strategies are rarely actually applied because actual planning and design projects need to consider issues such as applicability, economy, and feasibility [44–46]. For example, in hot and dry places, large-scale use of vegetation or water bodies is expensive or impractical. Furthermore, although changing the geometry of outdoor space has been found to be an effective passive cooling strategy, in real projects, there is often a limit to the extent to which the geometry of outdoor spaces can be changed. In addition, there are differences in the promotion effect of adjustment strategies on thermal comfort under different climates

and different functional types of outdoor space. Therefore, urban outdoor spaces should be refined and classified according to climate conditions, functional types, and restrictions, and studies should be carried out separately to propose thermal comfort improvement strategies to provide scientific references for actual projects.

7. Conclusions

The study of thermal comfort in urban outdoor space is an important research topic and is still under continuous development. This paper reviews urban thermal comfort evaluation methods, influencing factors of outdoor thermal comfort, and strategies to improve urban outdoor space thermal comfort. This paper summarizes the development and classification of outdoor thermal comfort indices, and summarizes the influencing factors from five aspects: urban climate conditions, microclimate conditions, physiological factors, psychological factors, and social and cultural factors, and discusses the mitigation strategies of urban geometry, vegetation, surface materials, water bodies. The following conclusions can be drawn:

(1) The neutral temperature in the tropical climate zone is the highest, and that in the continental climate zone is the lowest.
(2) Most studies have found that solar radiation has a greater impact on human thermal comfort than other microclimate factors. This feature is especially obvious in arid and cold climatic zones.
(3) Most studies have found that weight and skin color have a low correlation with thermal sensation, but gender and age lead to differences in thermal perception. Females are more sensitive to thermal discomfort than males, and younger people are more sensitive to heat discomfort than older people.
(4) In hot summers, compact spaces have a better urban thermal environment than open spaces. And in winter, wide streets are more comfortable than compact streets because more solar radiation is needed.
(5) Vegetation improves the urban microclimate, lowers air temperature, and increases humidity through transpiration, shading, and changing wind speed. The effect is related to the characteristics, location, and form of vegetation.
(6) The effect of reflective materials is not consistent in theory and practice. Some studies think that they can significantly reduce air temperature. In contrast, others believe that the effect is small or negligible, which needs to be further verified by field measurement and a questionnaire survey.
(7) Water bodies have a cooling effect on the urban thermal environment, but they also increase humidity and affect thermal comfort. The cooling effect of water bodies depends on a variety of factors, such as their size, shape, location, and surrounding environment.
(8) The effect of different adjustment strategies varies depending on site, time, and climate conditions, but generally speaking, changing the geometry is the more effective method, followed by increasing vegetation and using water bodies.

Studies of thermal comfort in urban outdoor spaces have been biased towards common climate areas and have ignored needs under extreme climate conditions. A more in-depth exploration of the thermal adaptation mechanisms in these areas is needed. Evaluation models need to be revised and calibrated to take into account factors in different regions and climates to make them more accurate and applicable. Although there are many design strategies to improve thermal comfort, their application in actual projects is limited by various factors. Therefore, for different climate and spatial function types, it is necessary to refine the classification and propose corresponding improvement strategies to scientifically guide the planning and design of actual projects.

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Abbreviations

ET	Effective Temperature	COSMO	Comprehensive Outdoor Scale Model
HSI	Heat Stress Index	EBM	Energy balance model
WBGT	Wet Bulb Globe Temperature Index	CFD	Computational fluid dynamics
DI	Discomfort Index	IZA	Thermal comfort Index for cities of Arid Zones
HI	Heat Index	MTSV	Mean thermal sensation vote
THI	Temperature–Humidity Index	ETU	Universal effective temperature
AT	Apparent Temperature	MOCI	Mediterranean Outdoor Comfort Index
WCI	Wind Chill Index	T_{mrt}	Mean radiant temperature
WCT	Wind Chill Equivalent Temperatures	CK	COMFA-kid
NWCT	New Wind Chill Equivalent Temperature		
ET*	New Effective Temperature	SVF	Sky view factor
SET*	New Standard Effective Temperature	H/W	Height-to-width ratio
OUT_MRT	Outdoor Mean Radiant Temperature	TCR	Thermal comfort ratio
OUT_SET*	Outdoor Standard Effective Temperature	NDVI	Normalized difference vegetation index
PMV	Predicted Mean Vote	TSG	Trees, shrubs, and grass
PPD	Predicted Percentage of Dissatisfied	UIWB	Urban inland water bodies
PET	Physiologically Equivalent Temperature	HAM	High-albedo materials
MEMI	Munich Energy-balance Model for Individuals	UHI	Urban heat island
UTCI	Universal Thermal Climate Index	ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
TCV	Thermal Comfort Vote	ISO	International Standard Organization
TSV	Thermal Sensation Vote	BMI	Body Mass Index
TPV	Thermal Preference Vote		

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