

## A Periodic Clustering Review of Outdoor Thermal Comfort Studies in this Century for their Developing Trends

Jian Zhang, Feng Zhu, Yisha Liu, Xiaowei Shang, Fan Liu, Fanchun Liu, Binbin Chen, Siqi Wang\*

School of Civil Engineering and Architecture, Southwest University of Science and Technology, Mianyang, China.

### ABSTRACT

Outdoor thermal comfort (OTC) was significantly affecting human living qualities. Studies about them were popular in recent decades. They explored people's perception variations towards different thermal conditions. Most studies were conducted in similar ways. They collected data of subjects by questionnaire and of meteorology by instruments or sensors. Findings were acquired through statistical associating data of the two aspects, which is expressed by neutral temperatures (NT) etc. Since the development of techniques and the improvement of residents' needs, the studies in different periods varied technically. Some post-2020 studies involved an extra factor differing samples, e.g., age, origin, activity intensity etc., discovering NTs varying for either of the factor. They were rarely considered in studies during 2010s. This showed the periodic developments and changes of OTC studies, which is rarely significantly concluded and discussed previously. This article conducted a periodic clustering review of OTC studies published in this century. Selected papers were clustered into several groups regarding their properties. Some trends about their developments were found. They were directive for future studies of this topic.

**KEYWORDS:** Outdoor thermal comfort; Thermal comfort indices; Models; Thermal sensation vote; Köppen Climate Classification

### ABBREVIATION

ASV: actual sensation vote  
ANOVA: analysis of variance  
DSV: draft sensation voting  
DI: discomfort index  
DISC dyn: dynamic discomfort scale  
ET\*: effective temperatures  
HSV: humidity sensation vote  
KS test: Kolmogorov Smirnov test  
LIR: linear regression  
LOR: logistic regression  
LST: land surface temperature  
MRT: mean radiant temperature  
MWW: Mann-Whitney-Wilcoxon  
OCV: overall comfort vote  
OR: ordinal regression  
OT: operative temperature  
OTC: outdoor thermal comfort  
OTE: outdoor thermal environment  
PET: physiological equivalent temperature  
PMV: predicted mean vote  
PoR: polynomial regression  
PrR: probit regression

RSV: radiation sensation vote  
SEM: structural equation modeling  
SRL: solar radiation level  
SET\*: standard effective temperature\*  
SEM: structural equation modelling  
SSV: sun sensation vote  
RH: relative humidity  
T<sub>a</sub>: air temperature  
T<sub>g</sub>: global temperature  
TAV: thermal acceptability vote  
TEP: perceived equivalent temperature  
TCV: thermal sensation vote  
TSV: thermal sensation vote  
THI: temperature-humidity index  
TPV: thermal preference vote  
TSI: thermal sensation index  
UHI: urban heat island  
UTCI: universal thermal climate index  
V<sub>a</sub>: air velocity  
WBGT: wet bulb-globe temperature  
WPV: wind preference votes  
WR: weighted regression  
WSV: wind sensation vote  
Yds: sense of thermal comfort

## 1. Introduction

Outdoor thermal comfort (OTC) was frequently studied in recent decades since its significant effects on people's living qualities. Poor thermal comforts caused physiological imbalances [1], further resulting in health problems [2], low work efficiency [3], and even high mortality [4]. The studies mostly combined subjective response and objective meteorology, which provides directions for improving occupant comforts. There were certain modes for the studies [5]. Nevertheless, as the social development, studies in different periods varied slightly. This could be expressed in various technical aspects.

OTC studies usually found individual responses towards thermal environments. There were two aspects of data of required, subjective information (through questionnaire [6]) and the meteorology (through surveying sensors [7]). The thermal response was the key of questionnaire. It evaluates human sensations towards current meteorology numerically. There were various models developed indicating that, such as thermal sensation vote (TSV [8]), thermal comfort vote (TCV [9]), predicted mean vote (PMV [10]). Each model has its own scaling ways. For example, TSV (7 scales) was scaled from -3 (cold) to 3 (hot), while TCV (4 scales) was between 0 (comfortable) and 3 (uncomfortable). They were the standardised division methods in ASHRAE [11] or ISO [12]. Nevertheless, they could be also scaled differently. Yao et al. [13] and Kántor et al. [14] divided TSV into 5 and 9 levels respectively.

People's thermal perceptions were complexly affected by diverse factors. Various meteorology parameters and subjective factors were both influential [15]. OTC studies needed to consider them comprehensively for an exact evaluation. On the one hand, they could utilise various simple parameters multiply (i.e., air temperature,  $T_a$ ; globe temperature,  $T_g$ ; air velocity,  $V_a$ ; relative humidity, RH [16]). They were conducted by studies of early time [17]. On the other, there were complex indices, each one contains a variety of simple parameters, such as physiologically equivalent temperature (PET [18]) containing various meteorology parameters ( $T_a$  etc.) and diverse personal factors (clothing insulation [19] etc.). Any involved factor was impactful on thermal perceptions. The complex indices were more often used by studies in recent years [20].

Data of the two aspects were statistically correlated. This was helpful to find the meteorology condition best meeting occupants' needs, directing the designs of physical environments improving living qualities. As to studies via complex indices, neutral temperatures (NT, the temperature point with no thermal stress [21]) were their key findings (mostly 2010 – 2020). After 2020, there were more advanced methods used, resulting in novel findings [22]. In fact, OTC studies varied for periods technically, which results from the advancements of technologies and practical demands. This article reviewed them in this century by periodic clustering. Published papers in each 5 years were grouped as a cluster. The whole review was processed by the following steps:

- ✓ Finding out around 100 papers of OTC studies published in this century, they equally distributed in each period (5 years), such as nearly 20 from 2000 – 2004;
- ✓ Technically clustering them by various aspects, including thermal indices, thermal comfort models, findings etc.;
- ✓ Comparing them technically for different periods to conclude the development trends of this topic.

## 2. Methodology

This study reviewed peer-reviewed articles about OTC published in this century. They were provided by various official journals and publishers. The articles reviewed were mainly from journals such as *Building and Environment*, *Science of The Total Environment*, *Energy and Buildings*, *International Journal of Biometeorology*, and *Journal of Thermal Biology*, which are scientific journals from mainstream publishers. The journal with the largest number of publications included *Building and Environment* (33), followed by *Sustainable Cities and Society* (10), *International Journal of Biometeorology* (10), and *Energy and Buildings* (6).

All articles were clustered into five groups regarding their periods. Each group contained papers from half a decade. They would be compared in various technical aspects. As on-site questionnaire implementations needed, all studies were conducted by field measurements. Nevertheless, all studies varied for the variation of contextual conditions. The variation might be significant for periods as technical developments in research. This study would comparably review OTC studies published in this century. They were clustered by techniques, including thermal

indices, models, cities, experiment sites, statistical models etc. These factors were comparatively reviewed by each five years. The process of resource selection (paper exclusion & inclusion) is illustrated in Fig. 1.

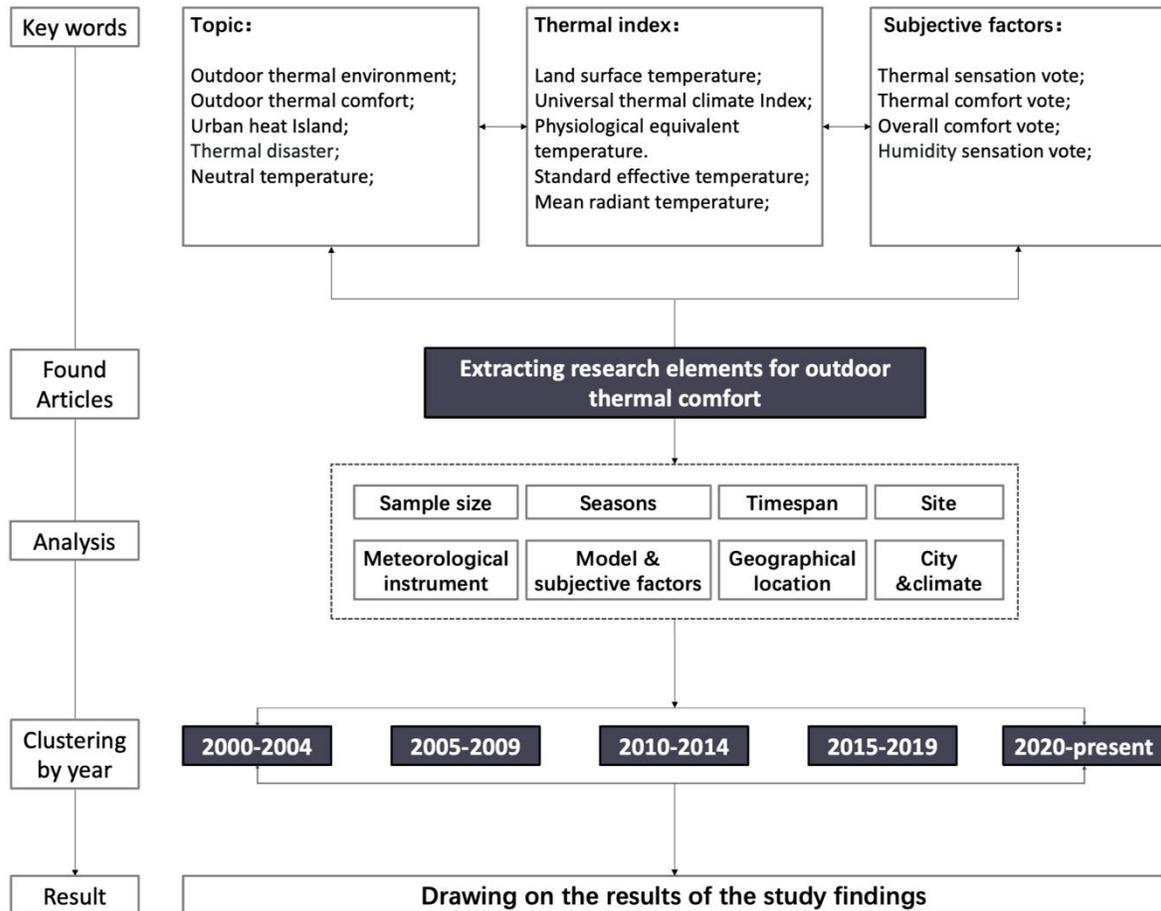


Fig. 1. Source of paper data and analysis process.

### 3. Results

#### 3.1. A general expression of reviewed studies

Tables 1 to 5 list the information of all selected studies regarding publishing years. They contained the properties of methodology, such as thermal indices and perceptive evaluation models. The following sections in this chapter would periodically compare and review them. TSV 5 in Table 1 represents 5-point scaling, TSV 7 represents 7-point scaling, same to the rest.

**Table 1**  
Selected articles between 2000 and 2004.

Resource	Seasons	Geographic location	City (climate)	Site	Sample size	Timespan	Thermal index	Model & subjective factors	Statistics
Sasaki et al.[23]	Four Seasons	Asia	Northern Japan (Dfb), (Dfa)	/	107	Three years	$T_a$ , $V_a$ , RH, radiation	Environment comfort level	Multiple linear regression

Fergus Nicol, [24]	/	Europe	Lyon (Cfa), Athens (Csa), Porto (Cfb) Lisbon (Csa), Gothenburg (Cfb), London (Cfb)	/	/	/	/	/	Multiple linear regression
Jendritzky et al.[25]	/	/	/	/	/	/	UTCI,MRT	PMV11	Data description
Westerberg et al.[26]	/	Europe	Göteborg(Cfb) Luleå	Park, a waterfront space, square, courtyard	/	/	T <sub>a</sub> , V <sub>a</sub> , radiation	/	Data description
Chrisomallidou et al.[17]	Autumn	Europe	Thessaloniki (Cfa)	Squares	312	September 2001	T <sub>a</sub> , V <sub>a</sub> , RH, Comfort, light	ASV5 and PMV5	Data description
Katzschner [18]	Summer	Europe	Kassel (Cfb), Milano (Cfa), Alimos, Athens (Csa)	Open space	/	/	PET	ASV5, PMV5	Data description
Nikolopoulou [27]	Summer and autumn	Europe	Athens (Csa)	Open space	418	summer and autumn 2001	MRT, T <sub>a</sub> , V <sub>a</sub> , RH	PMV11, ASV7, clo, physical activities	Data description
J.Spagnolo and de Dear [28]	Summer and winter	Oceania	Sydney (Cfa)	Airport	1017	/	OUT SET*, WBGT, T <sub>a</sub> , RH, MRT, V <sub>a</sub>	Clo	Linear regression
de Freitas [29]	/	Europe	Khalkidhiki (Cfa)	/	/	/	/	/	Data description
Nikolopoulou et al. [30]	Four Seasons	Europe	Athens (Csa)	Open spaces	1500	1 year	T <sub>a</sub> , T <sub>g</sub> , V <sub>a</sub> , RH	ASV5, PMV11	Multiple linear and stepwise linear regression
Cena et al.[31]	/	/	Himalaya, Karakoram (Dfa)	mountain	57	1998 – 2001	ET*	TSV7,Clo, 5-point scale	Spearman Rank correlations; Chi-squared and Mann-Whitney tests
Ahmed [32]	/	Asia	Dhaka (Cfb)	Various spaces	1500	Two months	T <sub>a</sub> , RH	TSV7	Linear regression
Nikolopoulou et al.[33]	Spring, summer, and winter	Europe	Cambridge (Cfb)	Vegetation, square, Quayside	1431		T <sub>a</sub> , T <sub>g</sub>	ASV5, PMV16	Polynomial, linear regression
Jennifer Spagnolo and de Dear, [34]	Summer and winter	Oceania	Sydney (Cfa)	Sites with various land uses	1018	2 years	OUT_SET*	TSV7	Probit regression

Thorsson et al.[35]	Summer and autumn	Europe	Göteborg (Cfb)	Parks	300	4 months	MRT	ASV7, PMV18	Polynomial, linear regression
Stathopoulos et al.[36]	/	North America	Montreal(Dfb)	Downtown public open spaces	466	34 days	V <sub>a</sub> , RH, radiation, T <sub>a</sub> -T <sub>n</sub> & ET*	TSV5,WSV5, HSV5,RSV	Linear regression
Givoni and Noguchi [37]	Four seasons	Aisa	Yokohama(Cfa)	Trees and uncanopied spaces	/	1994 – 1995	T <sub>a</sub> , V <sub>a</sub> , radiation	TSV7	Linear regression
Katzschner [38]	Summer and autumn	Europe	Kassel (Cfb);	Open spaces	/	August 2004 – October	PET, V <sub>a</sub> , radiation	PMV5	Data description
Reiter [39]	/	Europe	Brussel(Cfb)	Urban public spaces	/	/	T <sub>a</sub> , V <sub>a</sub> , RH, radiation	Olgyay's Bioclimatic Chart	Data description
Westerberg [40]	Winter and summer	North Europe	Göteborg(Cfb)	Water front square, parks	600	2000 – 2001	/	Outdoor time spending, physical activities	Data description

**Table 2**  
Selected articles between 2005 and 2009.

Resource	Seasons	Geographic location	City (climate)	Site	Sample size	Timespan	Thermal index	Model & subjective factors	Statistics
Saito et al.[41]	Four seasons,	Asia	Fukuoka (Cfa)	Walkways	1184	Over a year	/	/	Multiple linear regression
H and S [42]	Spring	Europe	Lisbon (Csa)	Riverside pavement	91	2 years	PET, MRT, T <sub>a</sub> , V <sub>a</sub> , RH, radiation	TCV4	Linear regression
Nikolopoulou and Lykoudis [43]	Four seasons,	Europe	Athens (Csa) Thessaloniki (Cfa) Milan (Cfa) Fribourg (Cfb) Kassel (Cfb), Cambridge (Cfb) Sheffield (Cfb)	All kinds of spaces	10,000	July 2001 – September 2002	T <sub>g</sub> , T <sub>a</sub> , V <sub>a</sub> , RH, SET*	ASV5	Parallel probit analysis
Zambrano et al.[44]	Spring	South America	Rio de Janeiro (Aw)	Squares	40	A day	T <sub>a</sub> , V <sub>a</sub> , T <sub>g</sub> , RH	PMV7, ASV, DISC	Multiple linear regression
Nicol et al.[45]	Four seasons	Europe	Manchester (Cfb)	Gardens, squares, streets	9189	August 2004 – May 2005	V <sub>a</sub> , solar radiation, RH, T <sub>a</sub> , T <sub>g</sub>	WSV7, TSV7, LSV5	Multiple linear regression
Monteiro and Alucci [46]	Summer and winter	South America	Sao Paulo (Cfa)	Roof, canopied spaces	886	Two years	NET, operative	PMV7	Data description

							temperature		linear regression
Bouyer et al. [47]	/	Europe	Paris (Cfb) Istanbul (Cwa)	Stadia	/	/	PET, T <sub>a</sub> radiation	PMV	Data description
Walton et al. [48]	autumn	Oceania	Wellington (Cfb)	Parks	649	9 months	V <sub>a</sub> , MRT and T <sub>g</sub>	TSV7	Linear regression, T test
Gaitani et al. [49]	Summer	Europe	Athens (Csa)	Residential areas	/	days	/	TSV7	Multiple linear regression
Kántor et al. [50]	Summer	Europe	Szeged (Cf)	Squares	844	August – September	PET	ASV3, PMV7	Data description
Oliveira et al. [51]	Four seasons	Europe	Lisbon (Csa)	Walkway, sitting areas	1000	2 years	PET, T <sub>a</sub> , V <sub>a</sub> , RH, solar radiation	TSV5, WSV5, TPV5, WPV5	Data description
Lin [52]	Summer and winter	Asia	Taichung (Cwa)	Square	505	Two years	PET, T <sub>a</sub> , MRT	TSV7, attendance ratio	Linear regression
Velkov [53]	Summer	Europe	Craiova (Cfa)	Unirii Street/ Mihai Viteazu Plaza vertical		/	PET	PMV7	Linear regression
Lin et al. [54]	Summer and winter	Asia	Central Taiwan (Cwa)	Outdoor spaces	1644	/	PET, SET*	TSV7	Polynomial fitted curves
Aljawabra and Nikolopoulou [55]	Summer and winter	North America	Marrakech Phoenix-Arizona (Bsh)	Urban spaces	429	Two years	radiation	ASV5, PMV5	Data description
Katerina et al. [56]	Summer	Europe	Athens (Csa)	/	/	Three months	T <sub>a</sub> , solar radiation, V <sub>a</sub> , RH, LST, TSI	ASV5	Data description
Lin [57]	/	Asia	Taiwan (Cwa)	Campus	1644	2 years	PET	TSV7	Polynomial fitted curves, linear regression
Sangkertadi et al. [58]	Summer	Asia	Manado (Af)	Concrete, asphalt, soil, grass, brickwork, and tile	24	June	LST, V <sub>a</sub>	PMV9, DISC	A regression model called dynamic discomfort scale (DISC dyn)
Sasaki et al. [59]	Summer	/	/	Trees, pond, asphalt	10	2008	SET*, PET	PMV7, TCV7	OMO model

Kántor et al.[60]	Spring	Europe	Szeged (Cf)	Campus, parks, square	/	April – May	T <sub>a</sub> , V <sub>a</sub> , RH, radiation	PMV7	Linear regression
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**Table 3**

Selected articles between 2010 and 2014.

Resource	Seasons	Geographic location	City (climate)	Site	Sample size	Timespan	Thermal index	Model & subjective factors	Statistics
Cheng et al.[61]	Summer and winter	Asia	Hong Kong (Cwa)	Square, campus	286	A year	PET	TSV7, PMV7	Polynomial fitted curves, Linear regression
Tseliou et al.[62]	Four seasons	Europe	Athens (Csa) Thessaloniki (Cfa), Milan(Cfa), Fribourg(Cfb),Kassel(Cfb), Cambridge(Cfb), Sheffield(Cfb)	outdoor space	9189	/	PET, THI,wind chill index (K)	ASV5	Linear regression
Lin et al.[19]	Summer and winter	Asia	Taichung (Cwa), Yunlin (Cwa), Chiayi (Cwa)	Street and park	1644	A year	SET*, T <sub>a</sub> , MRT	TSV7, clothing	Linear regression, probit analysis
Shimazaki et al.[63]	Summer	/	/	experimental site	57	July	SET*, T <sub>a</sub> , solar radiation	TSV7, TCV5, PMV	65 MN model
Lin et al.[64]	Spring, summer, winter	Asia	Taichung (Cwa)	Parks	/	August 2008 to October 2009	PET, MRT, T <sub>a</sub>	/	Polynomial fitted curves
Ng and Cheng [65]	Summer and winter	Asia	Hong Kong (Cwa)	Urban	2702	November 2006 to August 2007	PET	TSV7	Linear regression, logistic regression analysis
Makaremi et al.[66]	Summer	Asia	Putra (Af)	Campus	200	March – April	PET	TSV5, TCV5	Data description
Xi et al.[67]	Summer	Asia	Guangzhou (Cfa)	Campus	21	July 2010	SET*, MRT	TSV7,TCV5	Linear regression
Bröde et al.[68]	Summer and winter	South America	Curitiba (Cfb)	Street	1654	January & August	UTCI,	TSV7	Data description
Yang et al.[69]	Summer, autumn	Asia	Singapore (Af)	resting places	2036	August 2010 – May 2011	Operative temperature	TSV7, HSV5, WSV5, SSV5	Linear regression, probit, logistic regression analysis, ManneWhitney test
Pantavou et al.[70]	Summer, autumn, winter	Europe	Athens (Csa)	Square, street	1706	July, October 2010 &	UTCI, MRT, T <sub>g</sub>	TSV7	Linear regression, ANOVA,

						February 2011			ordinal regression
Cohen et al.[71]	Summer and winter	Asia	Tel Aviv (Csa)	Park, square, street	/	2007 – 2011	PET	TSV9	Linear regression, ANOVA test, TUKEY’S-B (equal variances assume) test
Lin et al.[72]	Summer and winter	Asia	Chiayi (Cwa)	Park	1183	August 2009 – October 2010	PET	TSV, Attendance ratio	Linear regression, quadratic polynomial regression,
Tung et al.[73]	Summer	Asia	Taichung (Cwa), Yunlin (Cwa), Chiayi(Cwa)	Square	1644	/	PET	TSV7	Linear regression, quadratic polynomial regression
Md Din et al.[74]	Summer	Asia	Putrajaya (Af)	Urban	79	/	Discomfort index	TSV7,TPV	Linear regression
Lai et al.[75]	Spring, summer, autumn, winter,	Asia	Tianjin (Dwa)	Park	1565	March 2012 – January 2013	UTCI, PET	PMV7, TSV7, OCV3	Spearman Rank Order Correlation Coefficient, linear regression
Villadiego and Velay-Dabat [76]	Summer	South America	Barranquilla (Aw)	Residential community	781	January 2012	T <sub>a</sub> , solar radiation, RH, V <sub>a</sub>	TSV7, HSV7, WSV5, SSV5	ANOVA
Sangkerta di and Syafriny [16]	Summer	Asia	Manado (Af)	/	300	2011 – 2012	T <sub>a</sub> , V <sub>a</sub> , RH, T <sub>g</sub>	PMV7	Linear regression
Watanabe et al.[77]	Summer	Asia	Nagoya (Cfa)	Campus	42	August – September	SET*, UTCI	TSV7	Linear regression

**Table 4**  
Selected articles between 2015 and 2019.

Resource	Seasons	Geographic location	City (climate)	Site	Sample size	Timespan	Thermal index	Model & subjective factors	Statistics
Chen et al.[78]	Autumn, winter	Asia	Shanghai (Cfa)	Park	596	November 2014 – January 2015	PET	TSV7	Linear regression
Ruiz and Correa [79]	Summer, winter	South America	Mendoza (Bwk)	CBD	622	July 2010 – December 2011	T <sub>a</sub> , RH, V <sub>a</sub> , LST	ASV5	Linear regression

Xue and Xiao [80]	Summer	Asia	Dongguan (Cwa), Panyu(Cwa), Shunde(Cwa), Foshan(Cwa)	Park	945	July 2014, and August 2015.	PET	TSV9	Linear regression
Zhao et al.[81]	Summer	Asia	Guangzhou (Cfa)	Campus	1582	August – October	SET*	TSV7, APD, ASV	Multiple linear regression
Li et al.[15]	Spring, Summer, Autumn	Asia,	Guangzhou (Cfa)	Residential community	1005	January – September	PET	TSV9, TCV9	Sample size weighted regression, second-order polynomial
Kántor et al.[14]	Spring, Summer, Autumn	Europe	Szeged (Cf)	Squares, Playgrounds, Streets, Parks	5805	2011, 2012, and 2015.	PET	TSV9	Probit regression, Linear regression
Lucchese et al.[10]	Summer and winter	South America	Campo Grande (Aw)	Square	408	July – November 2015	PET, UTCI, TEP, Yds	PMV7	Multiple linear regression
Kruger and Drach [82]	Summer	South America	Rio de Janeiro (Aw)	CBD	985	2012 – 2015	UTCI	TSV7, DTS7	Multiple linear regression
Nasrollahi et al.[83]	/	Asia	Isfahan (Bwk)	square, palace, cathedral	291	One decade	PET	TSV7	Linear regression
Johansson et al.[84]	Summer	South America	Guayaquil (Af)	park, waterfront, squares, pedestrian arcade.	544	2009 – 2010	PET,SET*	TPV6,	Probit, quadratic polynomial regression, linear regression
Hirashima et al.[85]	Summer	South America, Europe	Belo Horizonte (Aw); Kassel(Cfb); Freiburg(Cfb)	Squares	/	2009 – 2010	PET	/	Ordinal logistic regression
Yao et al.[13]	Winter	Asia	Shanghai (Cfa)	CBD	/	December – February	PET	TSV5	Multiple linear regression
Chen et al.[86]	Spring, Summer, autumn, winter,	Asia	Harbin (Dwa)	Campus	31(follow-up /week)	A year	PET	TSV11, TCV7	ANOVA, TUKEYB test

Xie et al.[87]	Spring, Summer, autumn, winter,	Asia	Hong Kong (Cwa)	Campus	1107	March – December	Operative temperature, V <sub>a</sub> , MRT	TSV7, TCV5	ANOVA, linear regression
Fang et al.[88]	Summer	Asia	Guangzhou (Cfa)	Campus	1100	July	PET, WBGT, UTCI	TSV11	Linear regression, E functions
Cheung and Jim [89]	Spring, Summer, autumn, winter,	Asia	Hong Kong (Cwa)	Park	830	April – March	PET, UTCI	TSV7	Binary logistic regression
Xu et al.[90]	Summer and winter	Asia	Xi’an (Bsk)	Sidewalk, squares, pavilion	70	January, July	UTCI	TSV7	Linear regression, probit analysis
Lau et al.[91]	Summer	Asia	Hong Kong (Cwa)	CBD park	1917	June – September	PET	HSV7, TSV7, WSV7, SSV7	Linear regression
Sharmin et al.[92]	Summer; autumn	Asia	Dhaka (Cfb)	residential areas; commercial area	1302	2years	PET, MRT	TSV7	Linear regression, polynomial fitted curve

**Table 5**

Selected articles between 2020 and present.

Resource	Season	Geographic location	City (climate)	Site	Sample size	Timespan	Thermal index	Thermal comfort model	Statistics
SaRHadi and Rad [93]	/	/	/	Streets	500	/	/	/	structural equation modelling, SEM
Chen et al.[94]	Four seasons	Asia	Harbin (Dwa)	Square	2510	2years	SET*, UTCI, PET	TSV11, TCV7	Linear and probit regression
Huang and Peng [6]	Winter	Asia	Chongqing (Cwa)	Square	484	January	PET	TSV7, TCV5, OCV	Multiple linear regression
Zhang et al.[8]	Summer	Asia	Qingdao (Cwa)	Bus station	50	August	T <sub>a</sub> , RH	TSV7	T test
Yin et al.[7]	Summer, autumn, winter	Asia	Harbin (Dwa)	Commercial district	1632	Half-year	PET	TCV3, TSV11, TAV5	Polynomial fitted curve, probit analysis, linear regression
Tang et al.[22]	Summer	Asia	Guangzhou (Cfa)	Construction sites	1063	7 days	PET, UTCI, TSI, WBGT	TSV5	Linear regression, Polynomial fitted curve
Speak et al.[95]	Summer	Europe	Bolzano (Cfb)	/	755	2years	UTCI, MRT	TSV7, TCV7, Ftemp	Linear regression

Nasrollahi et al.[96]	Summer	Asia	Ahvaz, Iran (Bwh)	Urban canyons	257	6 days	PET	ENVI-met, TSV7,	Linear regression
Li et al.[9]	Summer	Asia	Wuhan (Cfa)	Residential areas	948	Half-year	/	TCV5, TSV7, HSV5, DSV5	Spearman correlation analysis
Lau and Choi [97]	Summer	Asia	Hong kong (Cwa)	Pedestrian streets, residential estates, parks	1842	4 months	UTCI	TSV 7, TCV5, AeSV, AcSV	Kolmogorov-Smirnov (KS) test, Spearman's rank correlation test, MannWhitney-Wilcoxon U test
Lam et al.[98]	Summer	Asia	Guangzhou (Cfa), Zhuhai (Cfa), Melbourne (Cfb)	Botanic gardens/ park, campus	7596	5 years	UTCI, T <sub>a</sub> , V <sub>a</sub> , RH, T <sub>g</sub> , MRT	TSV7, TPV3	ANOVA, linear regression
Lam et al.[99]	Summer	Asia	Guangzhou (Cfa), Zhuhai (Cfa), Fanyu (Cfa)	Campus	4267	1month	UTCI	TSV7, HSV5, WSV5	ANOVA, linear regression
Gachkar et al.[100]	Summer	Europe	Bolzano (Cfa)	Urban parks	775	2years	UTCI	TSV 7, TCV7	Linear regression
An et al.[101]	Winter	Asia	Beijing (Dwa) Xi'an (Bsk) Hami (Bwk)	Urban parks	1809	2years	PMV, PET, UTCI, NUTCI, UTCIR	TSV 5, TCV5	Data description
Aghamohammadi et al.[102]	Summer	Asia	Kuala Lumpur (Af)	Campus	392	3moths	PET	TSV7,TPV5,TAV 2,TCV5	Linear regression, polynomial fitted curve, probit analysis
Zhen et al.[103]	Spring	Asia	Xi'an (Bsk)	Campus	258	2moths	PET	TSV 7, TCV7	Linear regression, polynomial fitted curve,
Tang et al.[104]	Summer	Asia	Guangzhou (Cfa)	Campus	1102	1month	PET	hysiological strain index (PSI); TSV9,ASV9,HSV 9	Linear regression, E functions
Chan and Chau [105]	Summer	Asia	Xindu(Cwa)	Parks	581	1month	PET	TSV7,	Multiple linear regression
Xiong and He [106]	Winter	Asia	Chongqing (Cwa)	Streets	760	3 days	T <sub>a</sub> , RH, V <sub>a</sub> , T <sub>g</sub>	TSV7, TCV5	Kolmogorov Smirnov test , logistic regression analysis, Chi-square test, spearman 's rank correlation coefficient
Lau et al.[20]	Summer	Asia	Hong Kong (Cwa)	Variety resident, Urbanparks	1917	Jun – Sept,4month	PET	TSV7, HSV7, WSV7	Linear regression, ANOVA

Kumar and Sharma [107]	Summer	Asia	Safidon (BSh)	Stadium	100	Jul – Sept, 7days	SET*, UTCI, PET	TSV7, OCV	Linear regression, spearman
Xiong et al.[108]	Summer	Asia	Mianyang(Cfa)	Campus	1415	3 months	PET,Wat er	TSV7,TCV3	Linear regression

### 3.2. Methodological comparison for OTC studies in various periods

Methodologies of reviewed in studies towards periods are illustrated in Figs 2 – 10.

#### 3.2.1. Thermal comfort indices

There were a variety of indices used evaluating OTC. A few complex and novel ones were developed suiting the comprehensiveness of thermal perceptions and advanced techniques. Hence, slight difference emerged for the uses of indices in different ages; this is illustrated in Fig. 2. The complex indices, e.g., PET [94], contain several parameters. They were used by different studies. The usage of PET has been the highest among all indices since 2005. Its five-year maximum usage reached 73.7%.  $T_a$  was a simple and well adaptable meteorology that widely used before 2009 [43]. It frequently emerged in studies before 2005, with usage reaching 50%; yet a sharp decline after 2010. In addition,  $V_a$  [44] and RH [51] were also frequently used until 2010; but after that, the usage dropped to around 10%. As the time going, complex ones were increasingly preferred. PET was considered by 27 studies after 2015, such as Nasrollahi [96]. The usage of UTCI rose from 5% (pre-2005) to 40% (post-2020).

The periodic variation of index usage expressed the development trend of this topic. The complex indices contain several influencing parameters; they were able to evaluate thermal perceptions more exactly. The pursuit of higher result accuracy could explain the popularisation of complex indices in later studies.

A few recent studies used one extra factor as the variable, finding out different NTs resulting from that, e.g., age [103] and sport intensity [88]. In fact, the extra variables (age and physical activity) were contained in general PET calculation [109]. It was an interesting finding that different NTs caused by them. Anyway, the later studies were carried out more complexly. There were also studies using skin temperatures [8], which should be sensed by thermal imager [95].



than 90% of studies collected hundreds of sheets. A certain number of them achieved 1000 [97], even 3000 [98]. The questionnaire quantity was slightly different between various periods. Extreme large sample sizes (1500 or more) appeared after 2010. The post-2015 studies by Chen et al.[86] and Xu et al.[90] had sample sizes of less than 100, but they conducted multi-stage experiments with small-size samples, e.g., Chen et al.[86] followed up 31 people for up to a year, interviewing once a week. A few studies contracted a small number of volunteers for interviewing repeatedly [8]. This was capable to ensure a large number of sheets obtained despite of limited interviewees.

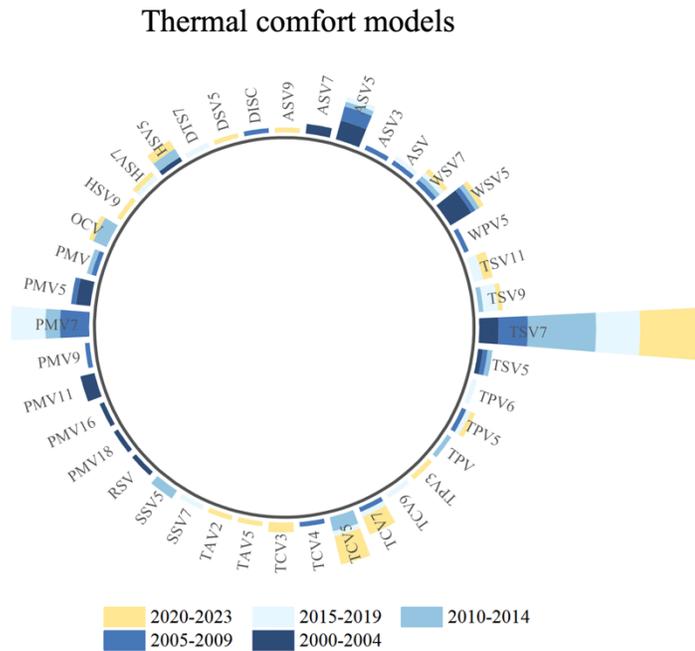


Fig. 3. Conducting frequencies of thermal comfort Model.

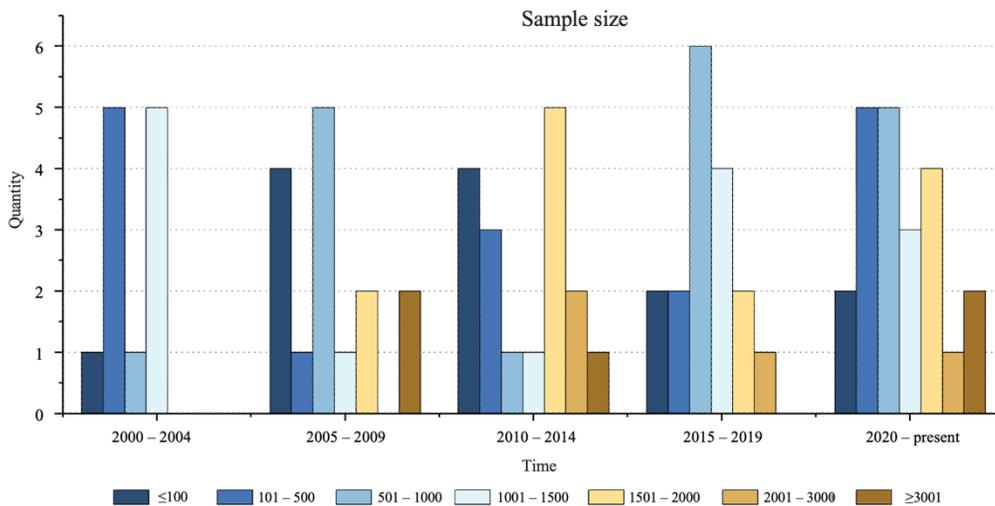


Fig. 4. Conducting frequencies of sample sizes.

### 3.2.4. Timespan

The field surveys were implemented in certain terms. There would be considerable weather variation. For instance, studies conducting in summers should be carried out in weathers from neutral (even cold) to hot. Hence, it had to took a long time, spanning from a few weeks [22] to a couple of years [95]. This is expressed in Fig.5. Generally, studies with a timespan of less than half a year account for 44% of the total number of studies, and studies spanning more than 3 years were the least. They all appeared after 2010, such as 2012 – 2015 [82].

The field works needed to ensure the sizes and statistical significances of data. There should be diverse contextual conditions involved, i.e., various meteorology causing multiple thermal responses. There would be poor statistical and incorrect results acquired if all surveys were implemented under similar conditions, such as only extreme hot weathers selected, proportional of people would vote hot (3) or very hot (4).

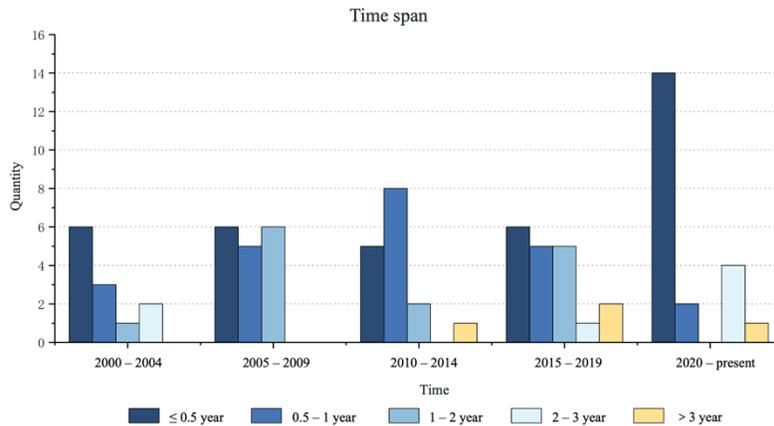


Fig. 5. Conducting frequencies of timespan.

### 3.2.5. Sites

Field surveys were carried out at outdoor spaces with certain ratios of people attending. Campuses [102], parks [71], and public squares [10] were popular sites selected by a number of studies. Campus, residential, and park studies had pronounced upward trends since 2020, with the number of campus studies going from 2 (pre-2005) to 6 (post-2020), and parks consistently having more studies, from 4 (pre-2005) to 7 (post-2015). Moreover, pedestrians might attend to commercial districts [7] and open spaces [17]. Open spaces were more special among the study sites because it was a broad description in early years that did not articulate a clear location for the study; therefore, plentiful before 2015 (25%). In addition, areas irrelevant to business were infrequently considered, such as mountains [31]. These cold areas were only involved by studies in early time, i.e., airport in Sydney.[28]. There were some special places, e.g., construction sites [22]. They were infrequently studied but necessary.

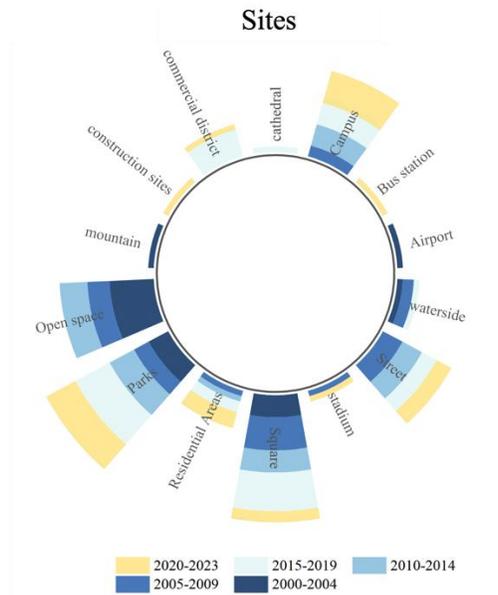


Fig. 6. Conducting frequencies of surveying sites.

3.2.6. Seasons

There are 4 seasons within a year. Any of them could be selected for investigating. There was little thermal stress in neutral seasons, spring and autumn, which is less surveyed. In contrast, most works were implemented during extreme seasons, summer [40] or winter [34]. Summers, nevertheless, were increasingly preferred as time going, and even 100% of studies on summer in 2010 – 2014. The phenomenon that four seasons were studied equally was witnessed at the early age of 2000s. Studies implementing in summers were the most proportional after 2020 [105]. It was followed by winter [106]; yet still less popular compared with earlier times [33]. That is to say, heat problems were becoming more and more serious.

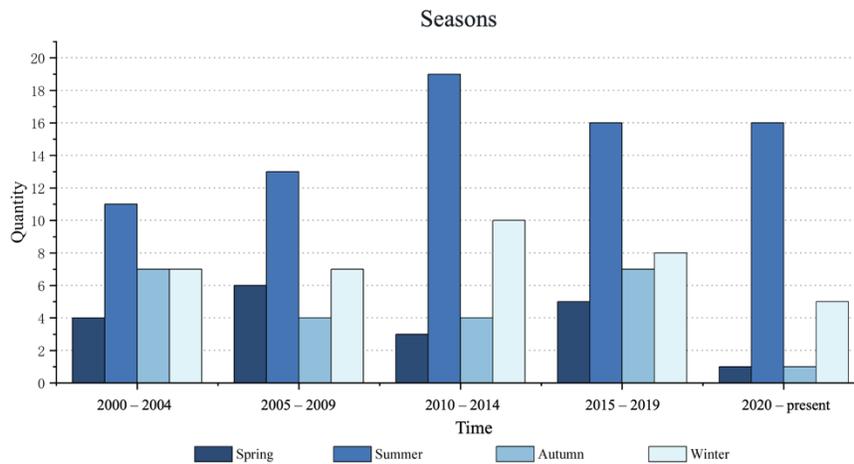


Fig. 7. Conducting frequencies of various seasons.

3.2.7. Geographical location

Researches on OTC around the world were dominated by Asia (54) and Europe (28), with most research in Europe was conducted at the beginning of this century [24], with the number of studies in the European region decreased over time and the number of studies in the Asian [32] increased from 3 to 19 (Fig. 8). There was little change in the number of studies in South America [44], North America [36], and Oceania [28]. There are no studies

on the African regions. The uninvolved populated regions, such as Africa, were necessary to be considered in the future.

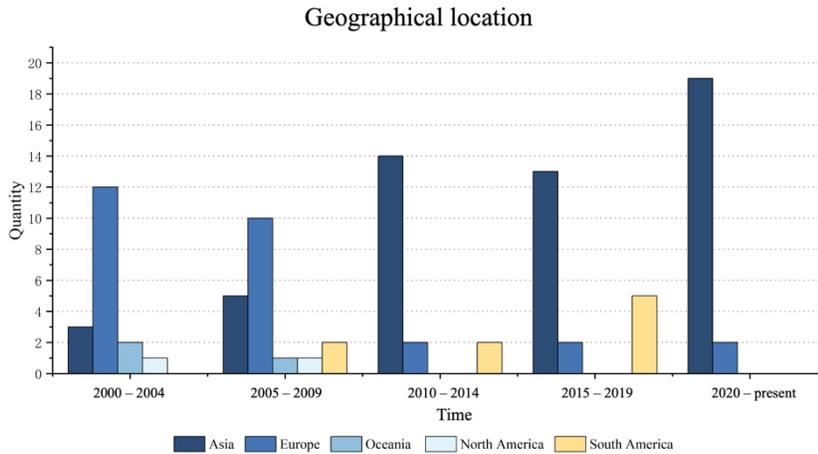


Fig. 8. Conducting frequencies of geographical locations.

### 3.2.8. Köppen Climate Classification

Articles in this review came from different climatic zones. Zone C (regarding Köppen Classification) had the largest share [32], accounting for 77.9% of the whole, with Zones A [58], B [55], and D [23] had a very small share, and the number of studies in every 5 years were lower than 5, and there was insignificant change over time revealed. Cfa (31) and Cwa (27) had the largest share in Zone C, followed by Cfb (17), and the number of studies in Cfb has gradually decreased, from 7 (2005 – 2009) to 2 (after 2020). There were essentially no studies conducted in Zone B in the early years, and almost all of the studies targeting Class B climate zones appear after 2015, such as Bwk [79] in 2015.

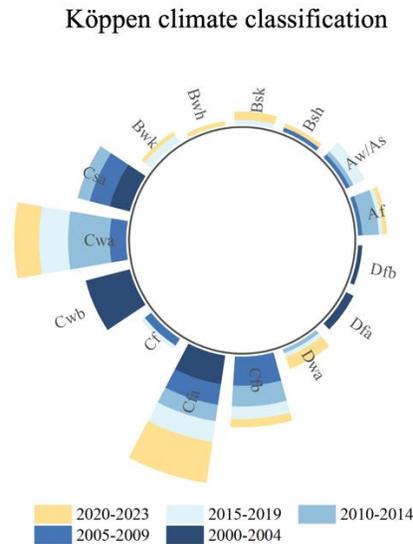


Fig. 9. Conducting frequencies of Köppen Climate Classification.

### 3.2.9. Statistical models

Statistical analyses were important in researches. Still some studies acquired their results without statistics, replaced by data description [38]. According to the statistical methods, (multiple) linear regression (MLR) was the key method [46], the usage of it increased in recent years (16 since 2020), followed by data description (9 before 2004). However, the method of data description was mostly utilised in early years. Polynomial regression [61] and

probit regression [90] were frequently selected as well. In recent years, more data analysis methods were involved, such as structural equation modelling (SEM [93]), analysis of variance (ANOVA [87]), etc., and the number of analysis methods has gradually increased. Although MLR was used the most frequently, people responses might non-linearly correlate with thermal indices. This caused stronger correlations by polynomial regression [33].

Many studies in early years used data description [39] to present their result instead of analysis. As time going, simply describing the data was no longer sufficient to present the complex results. The uses of data analysis methods was becoming more diverse and complex, ranging from MLR [30] to SEM [93].

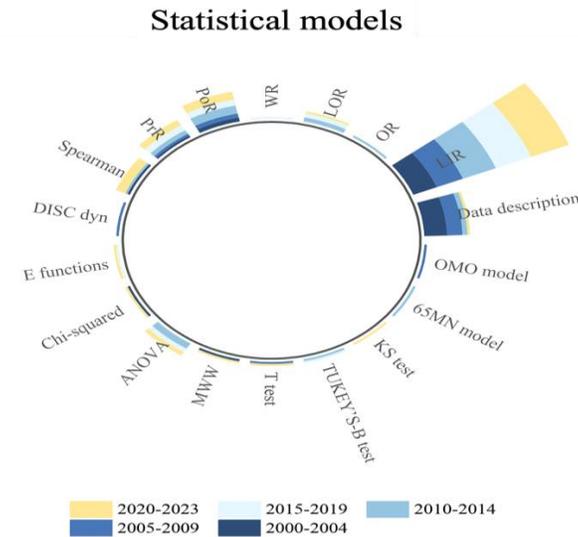


Fig. 10. Conducting frequencies of Statistical models.

### 3.2.10. Findings of reviewed studies

OTC studies aimed to find ways to adjust thermal environments improving residents’ living qualities. The studies aimed to find people’s responses towards various meteorological parameters. NTs were calculated by a high proportion of studies, especially 2015 – 2019 [81]. In early time, their responses were associated to diverse simple parameters multiply to differ relative significance of each one. Meanwhile, designers could set relevant environments for fulfilling their needs. Occupants would have certain behaviours to adapt to the extreme meteorology, such as attending canopied sites [64] and changing clothing conditions [111]. Post-2020 studies were relative complex. The subjective factor were associated with physical environments [112]; their responses were also differed by subjective factors, such as age [113] and thermal history [98]. People’s adaption activities should be more directive for design works to meet their demands.

### 3.3. Summary of the review

This chapter has comparatively reviewed OTC studies in different periods of this centuries in techniques. It was found, the studies in various periods varied technically. For example, studies in recent years have made relatively frequent uses of complex heat indices, extended thermal comfort models, and had larger sample sizes, yet the timespan of the studies has not increased significantly. This may be a result of technological advances and the fact that studies in recent years have been more efficiency-oriented.

## 4. Discussion

This study has concluded OTC studies clustering by periods. There were slight methodological difference between studies in different periods. The variation might result from the development of techniques.

#### **4.1. Thermal comfort indices and models**

There were a variety of thermal indices used. The usage of them varied periodically. Generally, comprehensive indices were increasingly popular [100]. This showed the development trends of OTC studies. Thermal comfort is a complex sensation that is affected diversely. It is hard to be evaluated accurately [24]. As the technical development, scholars were attempting to improving the accuracy. There were more scientific and advanced techniques developed. This could explain the popularisation of complex indices in later studies. There would be more comprehensive indices developed in future studies for accuracy enhancement.

#### **4.2. Timespan & Questionnaire**

There was no clear increasing trend in the timespan from the turn of the century to after 2020, and the overall time change has not increased over time; instead, studies within six months after 2020 were the most numerous [20], but shorter timespans tend to correspond to larger sample sizes, such as the 14-day study conducted by Lam et al.[99], which reaches a questionnaire size of more than 4,000. This was because of samples of different origins [99], there should be enough samples from each region. Except for the very few studies that were very long and also had large sample sizes. In terms of the number of questionnaires, more questionnaire counts of 1500 or more appeared after 2010, and even if there were studies with a smaller number of surveys, they were conducted to supplement the experimental data. Therefore, current studies had higher efficiencies. They could collect larger amount of data in short time.

#### **4.3. Köppen Climate Classification and geographic location**

Climatic divisions and geographic locations were dominated by Asia and Europe, with Europe dominated by Western Europe. Correspondingly, climatic zones are most numerous in Zone C, with Cfa, Cwa, being the most numerous. This might be caused by their complex climate, two extreme yearly seasons [114]. Zones A and E were permanently hot or cold.

#### **4.4. Seasons and research sites**

Most studies were conducted at city sites with high attending ratio of dwellers. Parks [115], streets [116], campuses [117], and squares [118] were crowd city places. Their high usages were easily understandable. The 4 yearly seasons used to be studied. Relatively, winters and summers were preferred since extreme weathers. Nevertheless, studies of recent years were more frequently carried out in summers. That is to say, heat stress resolution was increasingly needed, for the global warming [119].

#### **4.5. Future studies**

This review showed trends of OTC researches over 23 years since 2000 and provided a chronological cluster analysis of thermal indices, subjective models, and climate subregions in research methodology. The research on OTC has been fruitful in this century; however, nowadays, with the frequency of global extreme climates, more efforts are needed to cope with future climate change and the co-evolution of cities and villages. OTC studies aimed to improve human living qualities. The findings suggest that future studies to address following problems:

##### **1. Thermal comfort indices**

Complex indices were increasingly popular. They involved diverse elements being influential on people's thermal perceptions e.g., PET. Nonetheless, there were studies focusing on contexts differing by one aspects of the factors in the latest few years, such as sport intensity [104], age [113], wind conditions [87] etc. In fact, these parameters were all included in PET calculation. It might be unnormal if the emergencies of different thermal responses for the variation of either of the parameter. Therefore, there would be more technically advanced indices developed, that could accurately respond the effects of any thermal influencing factor, such as SET\* [84] and OUT-SET [120] developed from SET [121]. The effect of skin temperature [122] would also be attended.

##### **2. Thermal comfort models**

TSV and TCV were the most popular OTC models. They were more comprehensive than HSV and WSV. Therefore, they were used in a wider range of applications in recent years. There has been a preference for models of 7 points and above [103]. In fact, 9-scale models should be encouraged, as 3 (hot) and -3 (cold) were hard to evaluate perceptions in extraordinary meteorology [80]. Considering the direction of more refined and targeted design in the use of models, the integrated use of multiple models needs to be considered in the future [9]. When asking for volunteers to vote, make the vote more accurate, such as 0.1 [108] to assess perceptions more accurately, would be necessary.

### 3. Climate

Most studies were carried out at climate zones with both hot and cold stresses (Zone C in Köppen Classification [104], hot-summer & cold winter). Factually, thermal (heat) stresses emerged at most other zones (Zones A, B, & D [101]). They could be considered in future studies.

### 4. Geographical location

Studies were popular in various geographical regions in different periods. The exploring focuses transferred from the Europe [27] (12 studies from 2000 – 2004) to Asia [102] (19 studies from 2020 – 2023) as time going. However, still a broad spectrum of areas uninvolved, such as African and Australia. They could be significantly considered in the future.

### 5. Sites

There have been a wide range of outdoor sites surveyed, such as parks and campuses; they were important urban areas; rurally populated sites could be involved by future studies, such as CASC [123].

### 6. Statistical models

Nowadays, most of the studies used MLR [20] for data analyses, and some of them used a combination of several analysis methods [84]. However, on the basis of these methods, more analysis methods rather than MLR can be tried according to the characteristics of the data, e.g., SEM [93]. Meanwhile, in NT calculation, most reviewed studies used MLR, acquiescence linear correlation. Nevertheless, polynomial correlation was also possible [15], through more complex process of calculation.

## 5. Conclusion

This review has concluded OTC studies published in this century by periodic clustering. It was found that the studies varied technically by eras. This might result from technical developments and living standard improvements. Vital discoveries are expressed as follows:

- ✓ There were a variety types of thermal indices viable; complex indices (PET) were relatively frequently used later studies; there should be more advanced indices proposed for more accurate indication.
- ✓ Thermal evaluation models were generally standardised; they were also progressively improved through scaling extension for more accurate evaluating; their resolution should be standardised as 0.1 or less in the future.
- ✓ Most of the studies were concentrated Zone C in Köppen; future studies in Zone A, B & D should be strengthened.
- ✓ Focuses of OTC studies transferred from the Europe to Asia; but still needed for Africa etc.
- ✓ OTC has been studied in urban areas such as parks, campuses, and squares, with fewer studies targeting rural areas and specific locations (e.g., construction sites), which can be considered in future studies.
- ✓ More (complex) analyses models in addition to MLR could be considered in the future.

This study summarises the research methods and characteristics of OTC in this century. The clustering study found that with the development of techniques, these researches have different advances and developments and limitations in terms of thermal comfort indices, thermal comfort models etc.. They could be fulfilled in the future.

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### Conflict of interests

There is no conflict of interest in this study.

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