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Thermal comfort of healthcare facilities in China: A review

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ABSTRACT

In recent years, the study of thermal comfort has gained significant attention for its profound impact on human well-being and productivity. Addressing thermal comfort in healthcare environments has become increasingly important as public demand for improved healthcare standards increases and patients prioritize their overall experience during medical visits. This study explores advances in thermal comfort research in healthcare facilities, tailored to the specific characteristics of Chinese healthcare facilities. It covers various aspects, including China's five major climatic regions, different categories of healthcare facilities, distinct functional zones within healthcare facilities, and different demographic groups. Additionally, this study summarized thermal sensation data across diverse demographic groups from reviewed literature, analyzing median indicators of different groups. When compared with current standards, it appears that while these standards generally support the broad needs of healthcare facility occupants, they fall short of accommodating the detailed design requirements specific to environments of healthcare facilities. The study identifies shortcomings in domestic research and suggests future research directions. It provides valuable insights for optimizing healthcare facilities' designs and environmental parameters in accordance with evolving global standards in healthcare facility management in China.

Abbreviation list

AU	Autumn
C zone	Cold zone
ET*	Effective temperatures
FS	Four seasons
HSCW zone	Hot-summer and Cold-winter zone
HSWW zone	Hot-summer and Warm-winter zone
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor air quality
lx	Illuminance
M zone	Mild zone
met	Metabolic rate, W/m^2
ORs	Operating rooms
RH	Relative humidity
SC zone	Severe Cold zone
SM	Summer
SP	Spring
SPL	Sound pressure level
T_a	Air temperature (°C)
T_{acc}	Acceptable temperature (°C)
T_g	Globe temperature
T_n	Neutral temperature (°C)
T_o	Operate temperature (°C)
T_p	Preferred temperature (°C)
V_a	Air velocity
WT	Winter

1. Introduction

The Statistical Bulletin on the Development of China's Healthcare Industry reports that in 2022, the total number of medical visits in healthcare facilities nationwide reached 8.42 billion, with an average of 6.0 visits per capita to healthcare facilities. The total number of healthcare personnel in China reached 14.411 million [1]. Hospitals, as a category within healthcare facilities, demonstrate significantly higher energy consumption compared to other public buildings in China, with

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rates exceeding those of other building types by 1.6–2.0 times [2], particularly with electricity representing the largest proportion of hospital energy consumption [3]. This disparity in energy usage underscores the substantial energy demand within the broader category of healthcare facilities. Among various strategies to improve energy efficiency, enhancing the air conditioning systems emerges as a pivotal approach [3]. It is also essential to consider maintaining the thermal comfort of occupants [4,5]. Thermal comfort, considered one of the most critical factors for augmenting occupants' comfort and satisfaction in indoor environments, pertains to an individual's satisfactory perception of the thermal environment [6,7].

Presently, there are two main approaches for predicting indoor thermal comfort: the rational and adaptive thermal comfort approaches [8,9]. The rational or heat-balance approach is based on the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) proposed by Fanger [10]. This model primarily includes four environmental factors (air temperature, mean radiant temperature, air velocity, and relative humidity) and two non-environmental factors (clothing thermal resistance and metabolic rate). The adaptive approach emphasizes that when users feel thermal discomfort, they tend to achieve comfort through physiological, behavioral, and psychological adjustments [11–13].

Regarding climatic differences, Zheng et al. found that the neutral temperature of temporary buildings is influenced by climate zones [8]. Sun et al. [14] reviewed relevant studies on Chinese residential buildings and found variations in thermal neutrality across different climate zones. Zhang et al. [15] also suggested selecting appropriate evaluation models based on local climate conditions. China encompasses various climate types, divided into five climate zones for building thermal design: Mild (M) zone, Hot-Summer and Warm-Winter (HSWW) zone, Hot-Summer and Cold-Winter (HSCW) zone, Cold (C) zone, and Severe Cold (SC) zone [16]. The relevant standards for indoor thermal environments in China (e.g., GB 50189–2015 [17], GB/T 50,785–2012 [18], GB 50176–2016 [19], etc.) also specify thermal environment requirements based on these different climate zones. Therefore, the consideration of climatic background differences is crucial.

Chinese healthcare facilities are categorized into hospitals, primary healthcare facilities, professional public healthcare facilities, and other healthcare facilities [20]. According to the Statistical Bulletin on the Development of China's Healthcare Industry in 2022 [21], there are 1.0329 million healthcare institutions in China, including 37,000 hospitals. Hospitals are further classified into three classes: Class 1, Class 2, and Class 3, and each class is subdivided into A, B, and C categories, representing varying degrees of functional capabilities, facilities, and technical expertise. Among these hospitals, there are 1716 Class 3 A hospitals, which represent the highest level of facilities and expertise. From the perspective of functional areas, the "Code for design of general hospital" [22] specifies requirements for indoor heating, ventilation, and air conditioning (HVAC) systems, highlighting five key functional areas related to human thermal comfort: outpatient department, emergency department, inpatient department, operating department, medical technical department. The outpatient department includes areas such as waiting areas, offices, treatment rooms, and etc. The medical technical department encompasses the laboratory, pathology department, and various other laboratories. Each functional area has distinct requirements for the indoor environment, contributing to the complexity of healthcare facilities [6]. Moreover, thermal comfort serves as an essential design criterion influencing the healing process of patients, the health of medical staff and visitors [6], highlighting its significant impetus for in-depth investigation.

Numerous scholars from various countries have conducted field investigations to explore the thermal comfort of occupants in healthcare facilities. Yau and Chew [23] found Malaysian hospital staff prefer warmer temperatures than ASHRAE standards suggest. Similarly, Van Gaever et al. [24] noted discrepancies between HVAC standards and surgical staff's comfort. In a separate study, Derks et al. [25] suggested "slightly cool" conditions for nurses, rather than neutral. Recommendations include creating different thermal zones in healthcare facilities to accommodate varied comfort needs. Skoog et al. [26] observed seasonal differences in thermal perceptions between staff and patients. Rus et al. [27] highlighted the need for adjusting thermal settings for postpartum women's metabolic rates. Verheyen et al. [28] explored thermal comfort in various departments of Belgian healthcare facilities, finding PMV-PPD indices largely accurate except in neurology wards. However, several studies [23,27,29] identified inconsistencies between Thermal Sensation Vote (TSV) and PMV in hospitals, highlighting the complexity of accurately gauging thermal comfort in healthcare settings. These investigations collectively highlight the complexity of achieving thermal comfort in hospital settings, influenced by a spectrum of factors including climatic conditions, seasonal variations, distinct functional areas within hospitals, and the diverse characteristics of the occupant population. Understanding and addressing these nuances is crucial for optimizing thermal comfort and enhancing the overall well-being of healthcare facility occupants.

Despite existing review articles on thermal comfort of healthcare facilities [30–32], they predominantly focus on English-language literature. Feng et al. [6] observed that, in a synthesis of English publications on hospital thermal comfort from various countries, Chinese studies were among the top three in publication volume. Furthermore, Sun et al. [14] noted variances in indoor temperature and neutral temperature across different climatic zones in China. However, a comprehensive review that encapsulates the thermal environment and comfort in Chinese healthcare facilities, considering all five climatic zones and various categories of healthcare facilities, remains absent. This study aims to conduct a comprehensive literature review to summarize the current state of thermal comfort studies in Chinese healthcare facilities across multiple dimensions, including different climatic zones, categories of healthcare facilities, functional areas, and demographic groups. This study compares thermal sensations among different demographic groups and comparing these findings with existing standards. And we also examine various factors related to thermal comfort, such as physical environmental, physiological and behavioral factors. The goal is to provide insights for energy conservation in hospitals and to guide the future development of thermal comfort in healthcare environments.

2. Methods

A comprehensive literature review was conducted to identify all relevant publications on thermal environment and thermal comfort in Chinese healthcare facilities up to March 2024 (Fig. 1). The search was conducted through various online databases, including China National Knowledge Infrastructure (CNKI), Google Scholar, Scopus, and Web of Science to ensure a comprehensive and diverse collection of documents. Web of Science provides high-quality journal coverage with a focus on North American and English-language journals dating back to 1900, but with limited non-journal resources [33,34]. Scopus offers a broader range of peer-reviewed journals with extensive global coverage, including supplementary materials such as conference proceedings and books, primarily post-1996 [34,35]. Google Scholar broadens the scope further by indexing a wide range of non-traditional and online resources, including theses and non-peer-reviewed materials [36]. CNKI, the largest full-text academic information website available in China, is critical for accessing publications within China [15], ensuring comprehensive coverage of domestic research and providing insights into the specifics of thermal comfort in the Chinese healthcare environment that international databases may miss. Together, these databases form a robust literature search strategy that is essential for a thorough review of thermal comfort in healthcare facilities.

During the search process, keywords such as "thermal comfort," OR "thermal sensation," OR "thermal environment," OR "neutral temperature," AND "healthcare facilities," OR "hospital," OR "medical building," AND "China" were used to capture research literature related to the

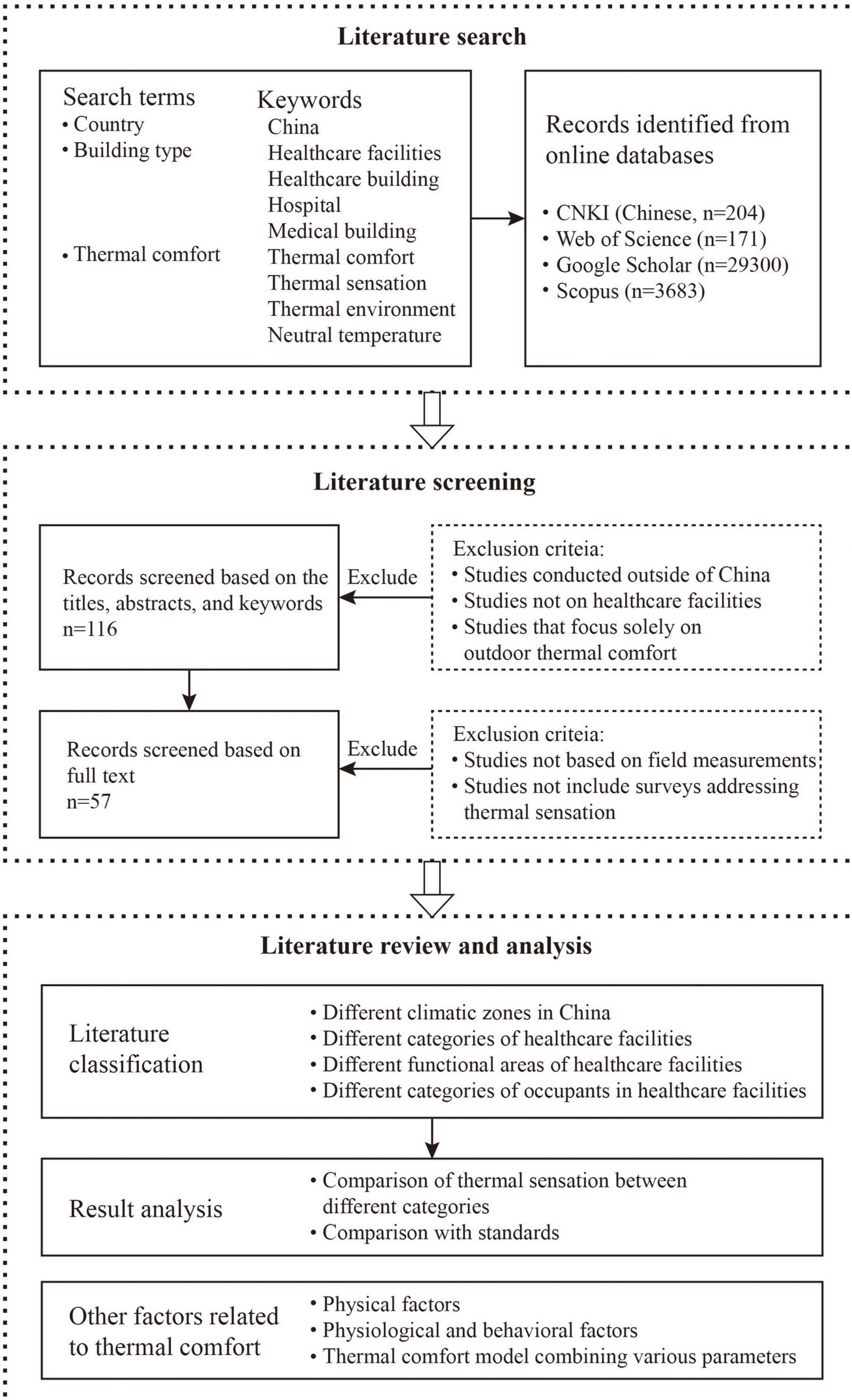

Fig. 1. Flowchart of the literature review.

thermal environment and comfort in Chinese healthcare facilities comprehensively. The search returned 204 results from CNKI Scholars (in Chinese), 171 results from Web of Science, 3683 results from Scopus, and 29,300 results from Google Scholar.

Subsequent to the preliminary search, a rigorous screening process was used to examine the titles, abstracts, and keywords of the retrieved articles to ensure alignment with the research topic of thermal comfort in Chinese healthcare facilities. A total of 116 articles were initially identified for review. A thorough review of the full-text content was then conducted using strict inclusion criteria: 1) studies based on field measurements, 2) surveys addressing thermal sensation. By adhering to these selection parameters and eliminating duplicate studies, 57 articles were deemed suitable for selection including 38 publications in Chinese and 19 publications in English, which covered journal articles, conference papers, and doctoral or master's theses.

3. Results from literature analysis

A statistical analysis was conducted on the temporal distribution of 57 reviewed literature related to thermal comfort of healthcare facilities in China (Fig. 2). The analysis revealed a notable increase in the number of published articles between 2018 and 2023, with a peak of 11 articles in 2022, representing a significant increase compared to previous years. Comparing this trend with international research on thermal comfort in healthcare facilities, as outlined in the literature review by Yuan et al. [6], international research on hospital thermal comfort began to significantly increase around 2012. This disparity highlights the relatively late start of thermal comfort research in Chinese healthcare facilities. Nonetheless, the current trajectory indicates a rapid development in this field, emphasizing the necessity for comprehensive review articles to effectively synthesize and analyze this expanding research area. This research provides a comprehensive review of the present status of thermal comfort research in Chinese healthcare facilities, exploring various aspects such as different climatic zones, categories of healthcare facilities, functional areas, and demographic groups.

3.1. Thermal comfort research on different climatic zones in China

Among the 57 articles reviewed, the research encompasses all five climatic zones in China: Hot Summer and Cold Winter (HSCW) zone, Cold (C) zone, Hot Summer and Warm Winter (HSWW) zone, Severe Cold (SC) zone, and Mild (M) zone (Fig. 3). The distribution of studies shows 28 articles (49 %) for the HSCW zone, 14 articles (25 %) for the C zone, 8 articles (14 %) for the HSWW zone, 3 articles (5 %) for the SC zone, and 1 article (2 %) for the M zone. Notably, 1 article covers two climatic zones, while 4 articles do not specify the research location. Table 1 tabulates articles containing detailed results, such as specific recommended thermal comfort temperatures for particular areas of healthcare facilities, revealing that nearly half of the studies focus on the HSCW zone, with relatively fewer studies conducted in other regions.

Research in the HSCW zone encompasses different categories of healthcare facilities, including general hospitals [37], nursing homes [38,39], community hospitals [40], and traditional Chinese medicine hospitals [41]. It also covers various functional areas such as outpatient departments (e.g., outpatient halls [42], waiting areas [43] and examination rooms [44]), inpatient departments (e.g., wards of different specialties [37,40,45] and nursing stations [46]), and operating departments (e.g., operating rooms [47]). Studies in the C zone are limited to general hospitals [48–50] and nursing homes [51] but are relatively comprehensive in terms of functional areas, including outpatient departments (e.g., waiting areas [48] and examination rooms [48]), emergency departments [52], inpatient departments (e.g., wards of different specialties [53–55] and nursing stations [49]), and operating departments [56,57]. Research in the HSWW zone only covers general hospitals [58,59] and is limited to functional areas such as outpatient departments (e.g., examination rooms [60], corridors [61] and waiting areas [62]) and inpatient departments (e.g., wards [63], ICUs [58] and nursing stations [64]). Studies in these three climatic zones include patients, staff, and visitors as the main research populations. In the SC zone, research is confined to general hospitals [65,66] and nursing homes [67], with a focus on inpatient departments and patients. The M zone has only one study, which researches thermal comfort in general wards of community hospitals [68], focusing on both patients and staff.

3.2. Thermal comfort research in different categories of healthcare facilities

Variations in environmental conditions and patient satisfaction exist across different classes of healthcare facilities in China [77,78]. Chinese healthcare facilities are categorized into hospitals, primary healthcare facilities, professional public healthcare facilities, and other healthcare facilities. Hospitals can be further categorized into general hospitals, traditional Chinese medicine hospitals, various specialized hospitals, etc. And they have different classes, such as Class 3 A, Class 2 A, and so on [20]. Among the 57 articles reviewed, the distribution of research in healthcare facility classes (Fig. 4) was as follows: 39 (68 %) of the articles focused on general hospitals, 5 (9 %) on nursing homes, 4 (7 %) on community hospitals, 1 (2 %) on traditional Chinese medicine hospitals, and 8 (14 %) did not specify hospital types or classes. Within the 39 studies conducted in general hospitals, 26 (67 %) of the articles concentrated on Class 3 A hospitals, 4 (10 %) on Class 2 A hospitals, and

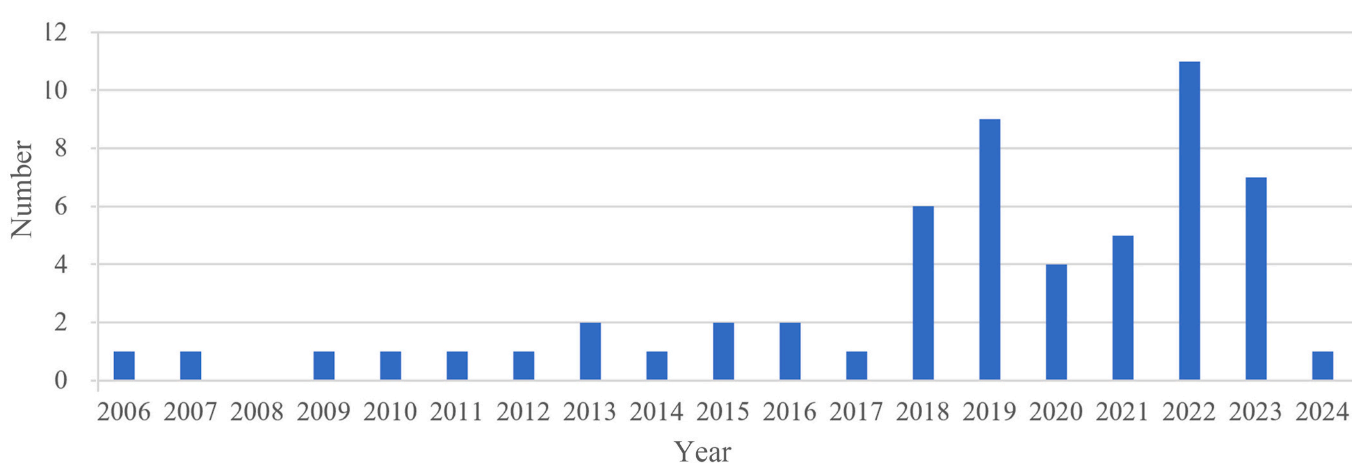

Fig. 2. The temporal distribution of reviewed literature.

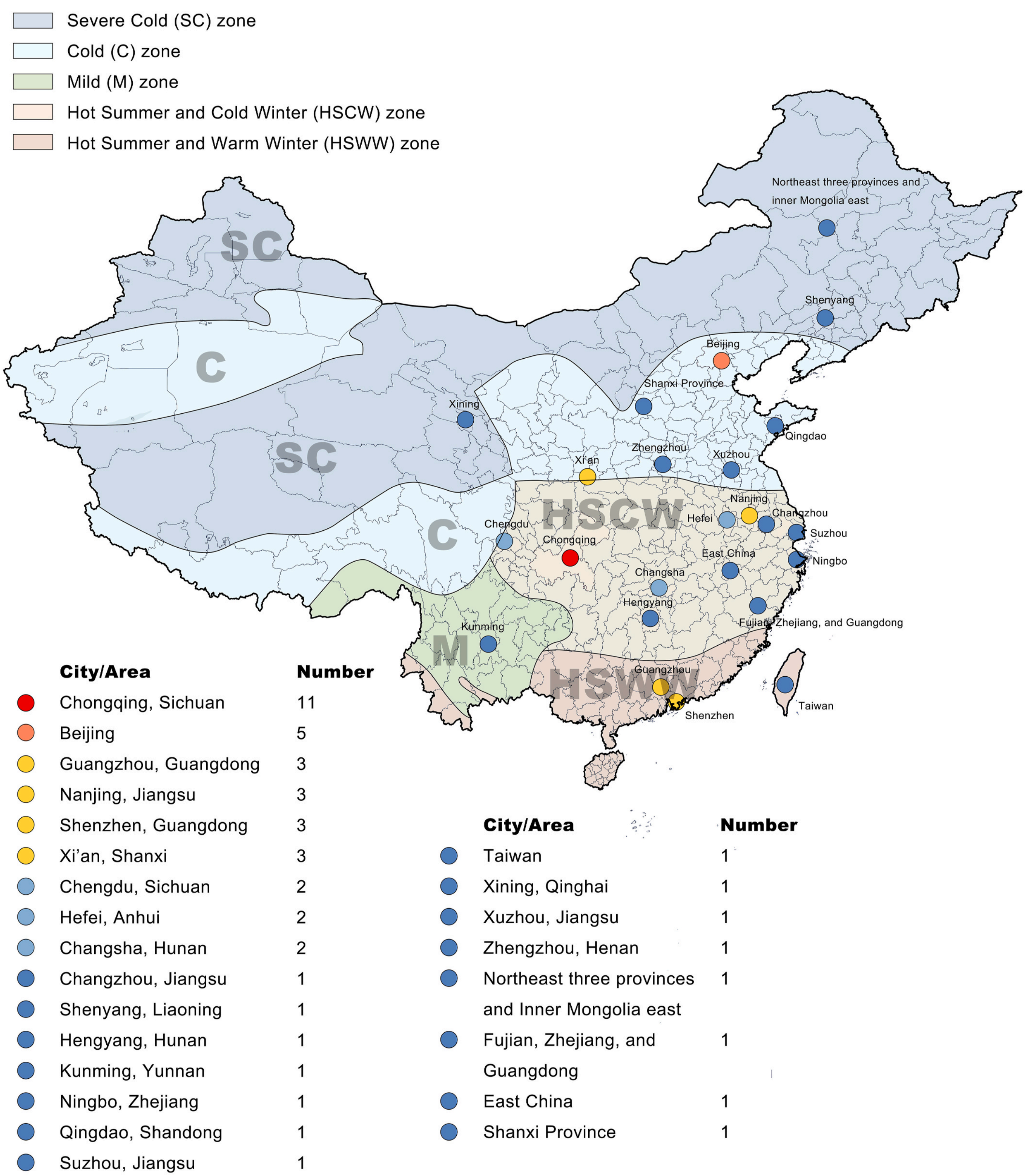

Fig. 3. The distribution of the reviewed studies in different climatic zones in China.

10 (26 %) did not specify hospital classes. It's evident that the majority of studies are concentrated in Class 3 A hospitals, indicating a significant concentration of research efforts within higher-tier healthcare facilities.

3.3. *Thermal comfort research on different functional areas of healthcare facilities*

Among the 57 articles reviewed, 34 (60 %) articles focused on thermal comfort in inpatient department, 13 (23 %) articles on thermal comfort in outpatient department, 5 (9 %) articles on thermal comfort in operating department, 1 (2 %) article on thermal comfort in emergency

Table 1
Data summary of reviewed studies in the different climatic zones.

Reference	Climate zones	Categories of healthcare facilities	Functional areas		Subjects	Number of valid questionnaires	Season	Demographic characteristics	Monitoring parameters	Thermal comfort indices	Approaches	Referenced standards	Main results
Lingkun Meng, 2017 [56]	C	Class 3 A hospitals	Operating department	Operating rooms	Postoperative medical staff	119	FS	Gender: male staff (42)， female staff (61) Age range: 27-42	Ta, RH, Va	PMV, TSV	Rational and Adaptive	GB50333-2002	For the current existing operating room thermal and humid environment: surgical gowns 0.44–0.64 clo can meets staff thermal comfort.
Siyou Wang, 2023 [54]	C	Class 3 A hospitals	Inpatient department	Waiting area and wards	Patients and visitors	613	SP and SM	Gender: male (43 %)，female (57 %) Age range: 18–70 Heigh：1.53m–1.89m	Ta, Tg, RH, Va, SPL, lx	SET, TSV	Rational	ISO 7730	The acceptable environmental ranges for outpatient settings: Temp. (24.21–30.46 °C), illuminance (116.98–339.20 Lux), sound levels (68.44–57.90 db). For wards: Temp. (24.09–27.87 °C), illuminance (68–380.50 Lux), sound levels (64.15–55.62 db).
Junpei Sa, 2021 [49]	C	Class 3 A hospitals	Inpatient department	Wards and nurse station	Patients, visitors and staff	110	SM and WT	Age range: 18-59	Ta，RH	TSV	Linear equation	ASHRAE 55	Consideration of three groups, T_{acc}: 21–23 °C (WT), 24–26 °C (SM). Humidity: Acceptable 30%–60 %, Ideal for rehabilitation and comfort 40%–50 %.
Wuxin Zheng et al., 2022 [51]	C	nursing homes	Inpatient department	Wards	The elderly	834	FS	Gender: male (44.6 %) female (55.4 %) Age range: ＞60	Ta, Tg, RH, Va	TSV, PD	Adaptive	ASHRAE 55-2013	Elderly in Xi'an adapt actively to indoor thermal environment, with higher acceptability and lower psychological expectations. T_{acc}:14.9°C–30.4 °C, T_n: 19.4 °C (WT), 22.6 °C (SP and AU), 24.1 °C (SM).
Shichao Zhang, 2023 [68]	M	Community hospitals	Inpatient department	Wards (including multiple departments)	Inpatients and staff	396	SM and WT	Gender: male (48 %)，female (52 %) Age range: more than 75 % were middle-aged and elderly people	Ta, Tg, RH, Va, CO_2, Total Volatile Organic Compounds	PMV, TSV	Rational and Adaptive	GB/T 50,785–2012, ASHRAE 55-2004	Patients T_n: Winter (19.86 °C), Summer (24.99 °C)
Shimin Liang, 2022 [69]	HSCW	Class 3 A hospitals	Inpatient department	Wards (including multiple departments)	Inpatients	609	SM and WT	Gender ratio: male: female (winter 1.8：1， summer 1.5：1) Age: ＞60	Ta, Tg, RH, Va, CO_2, T_{skin}	PMV, PMVe	Rational and Adaptive	GB/T 50,785–2012, ASHRAE 55	Patients' activity level significantly impacts clothing thermal resistance. WT: Lying (T_n 21.6 °C, T_p 22.4 °C),

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Table 1 (*continued*)

Reference	Climate zones	Categories of healthcare facilities	Functional areas		Subjects	Number of valid questionnaires	Season	Demographic characteristics	Monitoring parameters	Thermal comfort indices	Approaches	Referenced standards	Main results
								(winter 52 %, summer 43 %)					Sitting (T_n 16.6 °C, T_p 23.3 °C). Summer: Lying and Setting (T_n 25.4 °C, T_p 25.3 °C)
Jian Yu, 2017 [70]	HSCW	Class 3 A hospitals	Inpatient department	Wards (including multiple departments)	Patients, visitors and staff	1078	SM and WT	Gender: male (winter 60.1 %, summer 64.1 %) , female (winter 39.9 %, summer 35.9 %) Age range: 40–70(68.6 %, winter), 40–70 (69.7 %, summer)	Ta, Tg, RH, Va	PMV-PPD, TSV	Rational	GB/T 50,785–2012, ASHRAE 55	Patient and caregiver T_{acc}: 20.4°C-22.4 °C (WT), 24.6°C-26.5 °C (SM).
Hehua Feng, 2016 [71]	HSCW	Class 3 A hospitals	Inpatient department	Wards (including multiple departments)	Inpatients (predominantly elderly)	778	SM and WT	Gender ratio: male: female (winter 1.8 : 1) Age: > 50 (winter 61.2 %, summer 63.0 %), average age≈55	Ta, Tg, RH, Va	PMV-PPD, TSV	Rational	GB/T 50,785–2012, GB/T 18,977, ASHRAE 55	T_{acc}: 18.1°C-25.5 °C (WT), 21.9°C-28.4 °C (SM).
Xiang Liu, 2015 [72]	HSCW	Class 3 A hospitals	Inpatient department	Wards (including multiple departments)	Inpatients	682	SM and WT	Gender: male (winter 59.9 %, summer 59.7 %) , female (winter 40.1 %, summer 40.3 %) Age range: > 50 (winter 62.1 %, summer 53.1 %)	Ta, Tg, RH, Va	PMV-PPD, TSV	Rational and Adaptive	ISO 7730, ASHRAE 55	Comfortable temperature ranges for patients in different departments. Recommendations: Endocrinology, Gastroenterology, Cardiology, Oncology: 23.7°C-25.5 °C (SM), 22.8°C-24.2 °C (WT); General Surgery, Respiratory: 24.5°C-26.6 °C (SM), 23.6°C-25.3 °C (WT).
Ni Gong, 2013 [73]	HSCW	Class 3 A hospitals	Outpatient department	Waiting area and wards	Patients and visitors	743	SM and WT		Ta, RH, Va	TSV	Linear equation	ASHRAE 55	Hospital ward temperature control: Prioritize patient thermal comfort. Recommended ranges: Inpatient wards: 20–23 °C (WT), 24–26 °C (SM); Outpatient waiting areas: 17–20 °C (WT), 26–28 °C (SM). RH: 40%–60 % (WT), 60%–80 % (SM).
Shuting Cheng, 2023 [74]	HSCW	Community hospitals	Outpatient and inpatient department	Outpatient and inpatient department	Occupants	208	SM and WT	Gender: male (57.3 %) , female (42.7 %) Age range:	Ta, RH, Va, SPL, lx, CO_2	TSV	Linear equation	JGJ/T347-2014, ASHRAE 55	Suzhou Community hospitals: T_{acc}: 25.6–27.7 °C (SM), 13.2–16.8 °C (WT).

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Table 1 (*continued*)

Reference	Climate zones	Categories of healthcare facilities	Functional areas		Subjects	Number of valid questionnaires	Season	Demographic characteristics	Monitoring parameters	Thermal comfort indices	Approaches	Referenced standards	Main results
								mainly concentrated in 50–70					Respondents less satisfied with summer environment, showing inclination for summer optimization.
Xiaojing Sun, 2021 [75]	HSCW	Class 3 A hospitals	Inpatient department	Postpartum Recovery Center	Inpatient postpartum mothers, visitors and staff	123	SM and WT		Ta, RH, Va, SPL, CO_2, PM2.5	PMV	Rational	GB/T 50,785-2012	Chongqing obstetric postpartum room design: WT (T_a 21–23 °C, RH 50%–55 %), SM (T_a 25–27 °C, RH 55%–60 %)
Siyu Ma, 2023 [44]	HSCW	Public hospital (2), Private clinic (2)	Outpatient department	Dental treatment departments	Staff	333	FS	Gender: female (68.42 %) Age range: mainly concentrated in 20–30 medical staff (81.6 %), office staff (18.4 %)	Ta, Tg, RH, Va	PMV-PPD, TSV, aPMV, e PMV	Rational and Adaptive	ASHRAE 55	Comfort temperature varies with outdoor temperature: 20.77–22.26 °C (WT), 22.13–22.99 °C (SP and AU), and 23.03–23.76 °C (SM).
Ting Peng, 2021 [62]	HSWW	Class 3 A and 2 A hospitals	Outpatient department	Obstetrics Waiting area	Pregnant women and visitors	3054	FS	Age range: mainly concentrated in 20–30	Ta, Tg, RH, Va	PMV-PPD, TSV,	Rational	GB/T 50,785–2012, ISO 7726, ASHRAE 55	Considering both caregivers and pregnant women, T_{acc}: 18.49–24.81 °C (WT), 24.25–26.82 °C (SP), 24.13–27.13 °C (SM)
Jinyi He et al., 2021 [58]	HSWW	Class 3 A hospitals	Inpatient department	ICU	Patients and staff	339	FS	Number of people: patients in ICU (219), staff (110) Gender (number of people): Patients: male (133) female (86), Staff: male (53) female (57) Age range: patients:40–60 (49 %), staff: < 40 (60 %)	Ta, Tg, RH, Va	TSV	Linear equation	GB/T 50,785–2012, ASHRAE 55	Considering patients and staff comfort, health, and energy efficiency, ICU Thermal Control: Temp. 21°C-24 °C, RH 55%–70 %.
Ruey-Lung Hwang et al., 2007 [63]	HSWW	Medical center	Inpatient department	Wards at a medical center	Inpatients	927	SP and SM	Gender: male (54 %), female (46 %) Age: > 60 (48 %), average age (57)	Ta, Tg, RH, Va	PMV-PPD, TSV	Rational	ASHRAE 55-2004	Thermal comfort range for all year determined from thermal sensation and preference scales: 21.4–25.8 °C ET*. Narrower compared to Standard 55 comfort range.
Xiangfei Ji et al., 2020 [60]	HSWW	Hospitals (6)	Inpatient department	Obstetrics ward, Consultation room, nurse	Staff	114	SM	Age range: 20–50, average age (32.65)	Ta, Tg, RH, Va	PMV-PPD, TSV	Rational	ASHRAE 55-2004	Thermal comfort temp.: 22.83–25.94 °C (90 % satisfaction),

(*continued on next page*)

Table 1 (*continued*)

Reference	Climate zones	Categories of healthcare facilities	Functional areas		Subjects	Number of valid questionnaires	Season	Demographic characteristics	Monitoring parameters	Thermal comfort indices	Approaches	Referenced standards	Main results
				station, waiting area									21.74–27.03 °C (80 % satisfaction).
Jie Ni et al., 2024 [76]	HSWW	Not mentioned	Inpatient department	Department of Obstetrics	late pregnant women	1680	SM	Gender: female (100 %) Average age≈30.5	Ta, RH	TSV	Adaptive	GB/T 18,977-2003	Pregnant women's ATR upper limit: 24.4 °C. Higher ambient temperature, RH, maternal age, and prenatal BMI associated with an increased level of thermal perception.
Dajun Yao, 2018 [66]	SC	Class 2 A hospitals	Inpatient department	Wards	Inpatients, visitors and staff	948	SM and WT	Gender: Patients: male (55 %) female (45 %), Staff: female (100 %) , Visitors : male (75 %) female (25 %)	Ta, Tg, RH, Va	PMV, aPMV, TSV	Rational and Adaptive	ISO7730, ASHRAE 55-2004	Considering both patients and caregivers, Xining City general ward recommended temp.: 20–23 °C (WT), 23–26 °C (SM)
Haokun Li et al., 2022 [67]	SC	Rural Mutual Aid Homes	Inpatient department	Wards	The elderly	216	WT	Gender: male (45.45 %) female (54.55 %) Age range: 60–93, average age≈73.3	Ta, Tg, RH, Va	PMV, TSV	Rational and Adaptive	ISO7726, GB/T 50,785-2012	Elderly T_{acc}: 15.48–25.56 °C, T_p: 21.09 °C. The thermal resistance, T_n and thermal sensitivity of the clothing vary by age, notably >80 years.

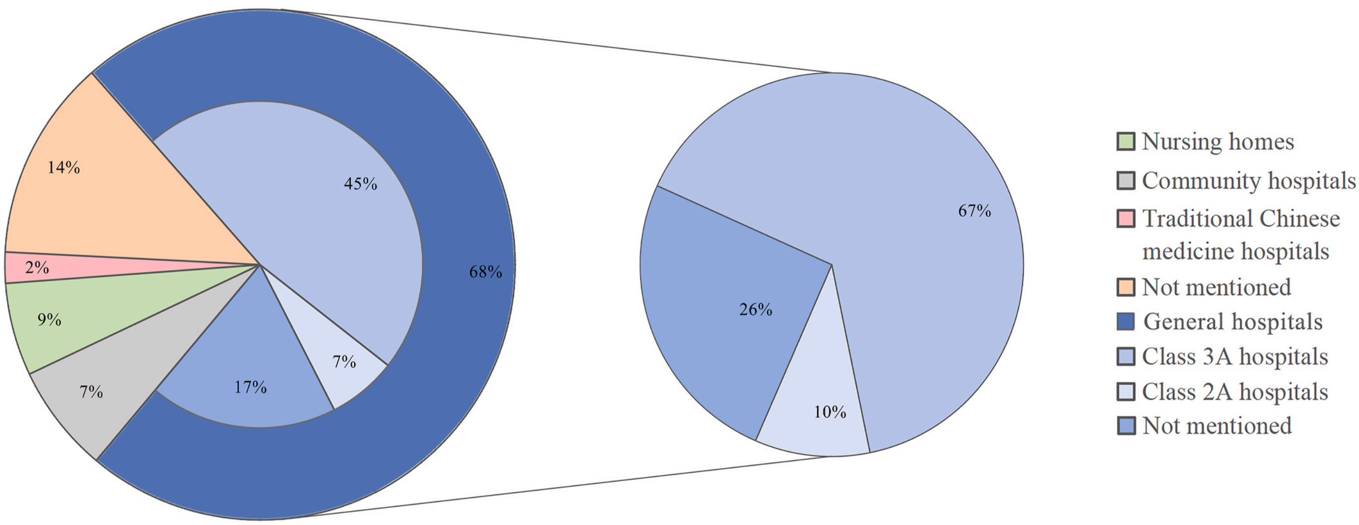

Fig. 4. The distribution of research in healthcare facility classes.

department. Studies on inpatient department of healthcare facilities include wards of different specialties [53–55], ICUs [58], nursing stations [49,64], and etc. Studies on outpatient department of healthcare facilities include waiting areas [48,54], hospital lobbies [42], medical streets [61], examination rooms [44,48], offices [60], and other regions.

Currently, there is a lack of research on thermal comfort in medical technical departments (laboratories, pathology departments, and various other laboratories) within Chinese healthcare buildings. Several factors may contribute to this gap. Medical technical departments often have unique environmental requirements tailored to specific medical procedures and equipment, prioritizing sterility, air quality, and safety over occupant thermal comfort. Furthermore, the interaction between various environmental factors in these departments can be complex, involving not only temperature and humidity but also air pressure and filtration, complicating thermal comfort research. In contrast to other functional areas where feedback on comfort is readily available, staff in medical technical departments may be less likely to report thermal discomfort due to their primary focus on tasks and the transient nature of their presence in these spaces. These factors collectively contribute to the limited research focus on thermal comfort in medical technical departments in Chinese healthcare buildings.

International research on thermal comfort in wards of inpatient department and operating rooms of operating department is prominent [6]. In China, studies on thermal comfort in healthcare facilities mainly focus on wards of inpatient department. Although there are relatively few studies on operating rooms in Chinese healthcare facilities, various aspects have been studied. For example, researchers explored physical methods to enhance thermal comfort for both patients and healthcare staff in the operating rooms. The adoption of preoperative warming techniques has proven effective in preserving body temperature for off-pump coronary artery bypass graft patients, enhancing their thermal comfort, diminishing the risk of hypothermia and its associated complications, and facilitating smoother postoperative recovery [79]. Composite clean operating rooms equipped with radiant panels have demonstrated the capability to regulate indoor temperature distribution, thereby enhancing the comfort levels of healthcare personnel. This setup also reduces the sensation of draft among the staff and significantly improves the Air Diffusion Performance Index from 44 % to 83 % [80]. Li [81] conducted a study on the temperature regulation in hospital operating rooms to achieve near-optimal comfort conditions. The findings indicate that with specific ambient temperatures and activity levels, by adjusting the thermal insulation of operating attire and setting indoor air velocity between 0.15 m/s and 0.25 m/s, and maintaining indoor design temperatures at 22 °C–23 °C, the PMV approaches 0, signifying peak human comfort. Liu et al. [82] explored the integration of a thermal comfort model (TCM) with CFD analysis in operating rooms, enhancing understanding of factors affecting thermal comfort. The TCM model calculates detailed indices like PMV and PPD, providing a comprehensive view of thermal comfort. This approach highlights the TCM model's effectiveness in analyzing thermal comfort.

Combining statistics based on categories of healthcare facilities reveals that in general hospitals, there are 25 studies on inpatient departments, 16 on outpatient departments, 5 on operating departments, and 1 on emergency departments. These studies primarily focus on Class 3 A general hospitals. In contrast, Class 2 A general hospitals have only 1 study on inpatient departments and 3 studies on outpatient departments (covering only waiting areas). Nursing homes have 4 studies on inpatient departments, while community hospitals have 2 studies on inpatient departments and 3 on outpatient departments. Traditional Chinese medicine hospitals have only 1 study on inpatient departments. Furthermore, 8 reviewed articles lack clear hospital information and were thus excluded from the statistics. Some articles cover multiple functional areas, and each area is counted separately, meaning a single article may be counted multiple times.

The findings indicate that research on various functional areas in general hospitals is mainly concentrated in Class 3 A hospitals, whereas studies on functional areas in Class 2 A hospitals are insufficient. Nursing homes and traditional Chinese medicine hospitals have studies focused solely on inpatient departments, lacking research on other areas. Although community hospitals' studies cover most functional areas, the overall number of studies is small. Given that community hospitals are the most numerous, this lack of research is particularly notable.

3.4. *Thermal comfort research on different people*

The study of thermal comfort in healthcare facilities includes research on three main categories of individuals: patients, staff, and visitors, with most research focusing on at least one of these groups. Among the 57 articles reviewed, 51 articles (89 %) investigate the thermal comfort of patients, 25 articles (43 %) investigate the thermal comfort of visitors, and 29 articles (51 %) investigate the thermal comfort of staff. This study categorizes conclusive literature related to these three groups in Tables 2–4. Research concerning patients primarily centers around inpatients, though studies targeting specific demographics are also existing. For instance, five articles [38–40,71,83] discuss the thermal comfort of elderly individuals, and four articles [55, 59,62,75] address the thermal comfort of pregnant and postpartum

Table 2
Thermal environment and thermal sensation of patients.

Reference	Climate zones	Categories of healthcare facilities	Functional areas	Demographic characteristics	Season		T_{acc} °C	T_n °C	T_p°C	Equation
Daju Yao, 2018 [66]	SC	Class 2A hospitals	Wards	Gender: male (55 %) female (45 %)	WT		21.1–23	22.61	22	PMV = $0.267T_o$-5.973 (R^2 = 0.85) TSV = $0.224T_o$-4.975 (R^2 = 0.88)
					SM		24.2–25.6	24.77	25	aPMV = $0.237T_o$–5.810 (R^2 = 0.93) TSV = $0.188T_o$-4.657 (R^2 = 0.96)
Ting Peng, 2021 [62]	HSWW	Class 3A & 2A hospitals	Waiting areas	Age range: mainly concentrated in 20–30	WT	Early pregnancy	18.49–24.81	19.94	23.05	PMV = $0.1852T_a$-4.5829 (R^2 = 0.4516) MTSV = $0.1472T_a$-2.9353 (R^2 = 0.5126)
						Mid-pregnancy	17.80–24.54	18.88	22.72	PMV = $0.2116T_a$-5.1719 (R^2 = 0.6573) MTSV = $0.1924T_a$-3.6327 (R^2 = 0.4962)
						Late pregnancy	17.53–23.74	18.07	21.77	PMV = $0.2050T_a$-4.8698 (R^2 = 0.7030) MTSV = $0.2391T_a$-4.3198 (R^2 = 0.4435)
					SP	Early pregnancy	24.25–28.08	25.36	25.72	PMV = $0.325T_a$-8.6856 (R^2 = 0.5918) MTSV = $0.3257T_a$-8.2584 (R^2 = 0.5451)
						Mid-pregnancy	24.20–27.24	25.09	24.94	PMV = $0.4105T_a$-10.772 (R^2 = 0.6771) MTSV = $0.3307T_a$-8.296 (R^2 = 0.6427)
						Late pregnancy	23.93–27.27	24.3	24.54	PMV = $0.5050T_a$-13.1130 (R^2 = 0.8740) MTSV = $0.3019T_a$-7.336 (R^2 = 0.7716)
					SM	Early pregnancy	23.73–29.50	26.47	25.87	PMV = $0.2799T_a$-7.554 (R^2 = 0.87) MTSV = $0.3471T_a$-9.1864(R^2 = 0.6209)
						Mid-pregnancy	24.13–28.82	25.53	24.41	PMV = $0.4131T_a$-11.205 (R^2 = 0.961) MTSV = $0.2646T_a$-6.7546 (R^2 = 0.799)
						Late pregnancy	20.99–27.13	24.41	22.66	PMV = 0.4419 T_a-12.11 (R^2 = 0.9609) MTSV = $0.2312T_a$-5.6447 (R^2 = 0.5711)
Jinyi He et al., 2021 [58]	HSWW	Class 3A hospitals	ICU	Number of people: 219 Gender (number of people): male (133) female (86) Age range: 40–60 (49 %)	FS		20.2–24.5	23.1	23.5	MTSV = 0.178T-2.937 (R^2 = 0.906) MHPV = 0.067RH4.104 (R^2 = 0.894)
Ruey-Lung Hwang et al., 2007 [63]	HSWW	Medical center	Wards	Gender: male (54 %) , female (46 %) age: >60 (48 %), average age (57)	Wt		20.7–25.4 (ET*)	22.9	23.91 (ET*)	
					SM		21.8–26.2 (ET*)	24.1	24.62 (ET*)	

(continued on next page)

Table 2 (*continued*)

Reference	Climate zones	Categories of healthcare facilities	Functional areas	Demographic characteristics	Season		T_{acc} °C	T_n °C	T_p°C	Equation
ShiminLiang, 2022 [69]	HSCW	Class 3A hospitals	Wards	Gender ratio: male: female(winter 1.8 : 1 , summer 1.5 : 1) Age: ＞60(winter 52 %, summer 43 %)	WT	Lying		21.6	22.4	TSV = 0.132T_o-2.852 (R^2 = 0.815)
						Sitting		16.6	23.3	TSV = 0.047T_o-0.779 (R^2 = 0.254)
					SM	Lying		25.4	25.3	TSV = 0.072T_o-1.827 (R^2 = 0.310)
						Sitting		25.4	25.3	TSV = 0.276T_o-7.003 (R^2 = 0.568)
Jian Yu, 2017 [70]	HSCW	Class 3A hospitals	Wards	Age range: 30-60	WT	All	18.1–25.5	21.4		PMV = 0.190T_o-4.060 (R^2 = 0.530) TSV = 0.158T_o-3.376 (R^2 = 0.870)
						Internal medicine department		21.2		PMV = 0.263T_o-5.545 (R^2 = 0.670) TSV = 0.122T_o-2.586 (R^2 = 0.853)
						Surgery department		21.5		PMV = 0.312T_o-6.633 (R^2 = 0.805) TSV = 0.141T_o-3.033 (R^2 = 0.717)
					SM	All	21.9–28.4	24.8		PMV = 0.208T_o-5.108 (R^2 = 0.715) TSV = 0.155T_o-3.841 (R^2 = 0.870)
						Internal medicine department		24.7		PMV = 0.193T_o-4.649 (R^2 = 0.725) TSV = 0.200T_o-4.939 (R^2 = 0.733)
						Surgery department		25.1		PMV = 0.329T_o-8.290 (R^2 = 0.706) TSV = 0.133T_o-3.340 (R^2 = 0.818)
HehuaFeng, 2016 [71]	HSCW	Class *3A* hospitals	Wards	Gender ratio: male: female(winter 1.8 : 1) Age: ＞50(winter 61.2 %, summer 63.0 %), average age≈55	WT		18.1–25.5	21.3	22.3	PMV = 0.159T_o-3.484 (R^2 = 0.733) TSV = 0.159T_o-3.376 (R^2 = 0.806)
					SM		21.9–28.4	24.8	25.1	PMV = 0.156T_o-3.858 (R^2 = 0.716) TSV = 0.155T_o-3.841 (R^2 = 0.870)
Xiang Liu, 2015 [72]	HSCW	Class 3A hospitals	Wards	Gender: male (winter 59.9 %, summer 59.7 %) , female (winter 40.1 %, summer 40.3 %) Age range: ＞50(winter 62.1 %, summer 53.1 %)	WT		20.1–23.8	22.53	22.8	PMV = 0.248 ET*-5.183 (R^2 = 0.92) TSV = 0.288 ET*-6.489 (R^2 = 0.78)
					SM		25–26.7	24.56	25.45	PMV = 0.286 ET*-6.937 (R^2 = 0.91) TSV = 0.25 ET*-6.141 (R^2 = 0.89)
Ni Gong et al., 2012 [45]	HSCW	Class 3A hospitals	Wards		WT		20.4–23.2	20.4		MTSV = 0.182T-3.714 (R^2 = 0.867) MHPV = 0.07RH-3.960 (R^2 = 0.861)
Shichao Zhang, 2023 [68]	M	Community hospitals	Wards	Gender: male (48 %) , female (52 %) Age range: more than 75 % were middle-aged and elderly people	WT			19.86	20.6	TSV = 19.232–0.968T_o (R^2 = 0.952) PMV = 19.229–0.986T_o (R^2 = 0.881)
					SM			24.99	24.3	TSV = 25.5–1.029T_o (R^2 = 0.990) PMV = 22.768–9.11T_o (R^2 = 0.988)

women.

3.5. Comparison of thermal sensation between different categories of occupants in healthcare buildings

The study of thermal sensations among different groups within healthcare facilities contributes significantly to the precision design of environments in healthcare facilities. The data from Table 2, Tables 3, and Table 4 were summarized to conduct a comparison regarding the thermal environment and sensation among different demographic groups in healthcare buildings. Table 5 presents the median values for various thermal perception parameters among patients, staff, and visitors. Fig. 5 (a) illustrates the variations in Neutral temperature (T_n) across Four seasons, winter, and summer for different groups. It is

Table 3
Thermal environment and thermal sensation of staff.

Reference	Climate zones	Categories of healthcare facilities	Functional areas	Demographic characteristics	Season	T_{acc} °C	T_n °C	T_p°C	Equation
Dajun Yao, 2018 [66]	SC	Class 2 A hospitals	Wards	Gender: female (100 %)	WT	18.45–21.22	20.00		PMV = 0.311T_o–6.305 (R^2 = 0.95) TSV = 0.401T_o- 8.024 (R^2 = 0.98)
					SM	22.65–24.82	23.49		aPMV = 0.471T_o–10.862 (R^2 = 0.88) TSV = 0.264T_o- 6.202 (R^2 = 0.87)
Xiangfei Ji et al., 2020 [60]	HSWW	Hospitals (6)	Obstetrics ward, Consultation room, nurse station, waiting area	Age: 20–50 Height (cm):151-173	SM	20.77–26.73	24.39	24.43	MTSV = 0.3212T_o-7.8326 (R^2 = 0.7621、P = 0.873、sig. = 0.01) PMV = 0.2856To-6.7828 (R^2 = 0.9275、P = 0.963、sig. = 0.00)
Jinyi He et al., 2021 [58]	HSWW	Class 3 A hospitals	ICU	Number of people: 110 Gender (number of people): male (53), female (57) Age range: < 40 (60 %)	FS	19.6–23.4	22.6	22.9	MTSV = 0.133T-2.522 (R^2 = 0.921) MHPV = 0.043RH-2.220 (R^2 = 0.859)
Siyu Ma et al., 2023 [44]	HSCW	Public hospital (2) , Private clinic (2)	Dental treatment departments	Gender: female (68.42 %) Age range: mainly concentrated in 20–30 medical staff (81.6 %), office staff (18.4 %)	FS	17.66–24.33	20.99		TSV = 0.15T_o-3.149 (R^2 = 0.871) PMV = 0.185T_o-4.034 (R^2 = 0.956)
					WT	20.77–22.26			ePMV = 0.785PMV aPMV=PMV/(1–0.34PMV)
					SM	23.03–23.76			ePMV = 0.687PMV aPMV=PMV/(1 + 0.128PMV)
					SP & AU	22.13–22.99			
Yukai Sun et al., 2023 [42]	HSCW	General hospital	Outpatient hall, waiting area, consultation room	Gender: female (80 %) age range: mainly concentrated < 40	SM & WT	24.1–25.6	25.6		

observable that patients consistently exhibit higher median neutral temperatures throughout the year and specifically during winter, compared to staff and visitors. This suggests that patients, who are less mobile and may have varying health conditions, require warmer conditions for optimal comfort. However, during summer, visitors prefer the warmest conditions, slightly higher than patients, while staff prefer a cooler environment. This variation underscores the importance of flexible climate control systems to cater to the differing comfort levels of each group during warmer months.

Despite the variations in the median Neutral temperatures among the three groups, Fig. 5 (b) reveals a closer approximation in their preferred temperatures (T_p). This similarity indicates that the expectations regarding thermal comfort in healthcare facilities are comparatively uniform across patients, staff, and visitors. Further examination through Fig. 5 (c) indicates that the range of acceptable temperatures (T_{acc}) for patients is broader than that for staff and visitors, both in winter and summer. This finding suggests that patients have a more flexible tolerance for temperature variations, which could inform the design and management of HVAC systems in healthcare facilities to better accommodate the diverse thermal comfort needs of all healthcare facility occupants.

3.6. Comparison with standards on thermal environment and thermal sensation

Despite the median values for the three groups in Section 3.5 falling within standard ranges, Fig. 5 illustrates that the data distribution for each group is not concentrated. This scatter is due to the inclusion of studies from different climatic zones and functional areas within the same dataset, leading to several data points lying outside the standard ranges. For instance, the "Code for design of general hospital (GB51039-2014)" [22] recommends that the temperature in waiting areas of outpatient department during winter should exceed 18 °C. However, research by Peng [62] identified the thermal comfort range for mid and late pregnancy in the obstetrics outpatient waiting area during winter as 17.80–24.54 °C and 17.53–23.74 °C respectively, which was outside the standard. Similarly, while the standard requires a winter ward temperature of 20.0–24.0 °C, studies by Yu [70] and Feng [71] reported a comfort range of 18.1–25.5 °C in general wards of inpatient department during winter.

Moreover, current standards (Table 6) specify HVAC temperature requirements for each department. They lack detailed regulations for specific functional areas, especially in summer. However, these standards lack detailed guidelines for specific functional areas within departments. While some wards, such as hematology wards, Grade IV burn wards, and allergy asthma wards, have more detailed standards from a medical perspective, the HVAC guidelines for other functional areas, especially during the summer, are less comprehensive. Although medical needs are the top priority in healthcare buildings, the importance of patient comfort and energy efficiency is increasingly recognized in light of societal development and the growing demand for well-being. Scholars have investigated the thermal comfort of occupants in specific functional areas within departments, revealing discrepancies between the occupants' temperature preferences and the existing regulations. For instance, Gong et al. [45] suggest for Chongqing hospitals, setting winter air conditioning temperatures and humidity levels at 20–23 °C and 40%–60 %, respectively, to balance comfort, health, and energy efficiency. These recommendations slightly diverge from the "Comprehensive Hospital Building Design Code", proposing for a 1 °C reduction in the indoor heating calculation temperature and a 10 % increase in the minimum relative humidity. Nonetheless, they are consistent with the humidity levels specified in the "Public Building

Table 4
Thermal environment and thermal sensation of visitors.

Reference	Climate zones	Categories of healthcare facilities	Functional areas	Demographic characteristics	Season	T_{acc}	T_n	T_p	Equation
Dajun Yao, 2018 [66]	SC	Class 2 A hospitals	Wards	Gender: male (75 %) female (25 %)	WT	19.5–23.3	21.11	21.4	PMV = 0.099T_o–2.086 (R^2 = 0.71) TSV = 0.124T_o- 2.617 (R^2 = 0.96)
					SM	23.5–26.4	25.19	24.4	aPMV = 0.288T_o–6.889 (R^2 = 0.85) TSV = 0.277T_o–6.978 (R^2 = 0.93)
Ting Peng, 2021 [62]	HSWW	Class 3 A & 2 A hospitals	Waiting areas	Age range: mainly concentrated in 20–30	WT	17.48–24.41	19.92	22.96	PMV = 0.1944T_a-4.5258 (R^2 = 0.8437) MTSV = 0.1864T_a-3.7137 (R^2 = 0.7615)
					SP	23.44–26.82	24.19	25.47	PMV = 0.4415T_a-11.482 (R^2 = 0.7556) MTSV = 0.2568 T_a-6.2116 (R^2 = 0.6037)
					SM	24.00–28.56	26.08	25.47	PMV = 0.3576T_a-9.6939 (R^2 = 0.9645) MTSV = 0.2794T_a-7.2859 (R^2 = 0.8118)
Jian Yu, 2017 [70]	HSCW	Class 3 A hospitals	Wards		WT	20.4–22.4	19.4		PMV = 0.178T_o-3.018 (R^2 = 0.826) TSV = 0.099T_o-1.918 (R^2 = 0.712)
					SM	24.6–26.5	25.5		PMV = 0.357T_o-8.524 (R^2 = 0.941) TSV = 0.296T_o-7.553 (R^2 = 0.915)
Ni Gong et al., 2012 [45]	HSCW	Class 3 A hospitals	Wards		WT	18.8–22.7	18.8		MTSV = 0.127T-2.383 (R^2 = 0.904) MHPV = 0.028RH-2.220 (R^2 = 0.547)

Table 5
Medians of different demographic groups in healthcare buildings.

	Patients	Staff	Visitors
T_n (Four seasons)	24.1	23.045	22.65
T_n (Winter)	21.25	20	19.66
T_n (Summer)	24.8	23.94	25.5
T_p (Four seasons)	24.105	23.665	24.4
T_p (Winter)	22.56	/	22.18
T_p (Summer)	25.05	24.43	24.935
T_{acc} (Four seasons)	21.1–25.6	20.77–23.76	21.92–25.405
T_{acc} (Winter)	18.49–24.54	19.61–21.74	19.15–23
T_{acc} (Summer)	22.815–27.765	22.65–24.82	24–26.5

Energy Design Standard" of Chongqing. This underscores the need for more precise and detailed standards to ensure both optimal patient comfort and energy conservation.

Healthcare facilities, with their multitude of departments, complex functional flows, and varied departmental requirements, necessitate a thorough investigation into diverse thermal comfort needs. Therefore, while existing standards may address the general thermal environment requirements in healthcare facilities, they fall short of accommodating the nuanced demands of refined thermal environment design within healthcare settings.

3.7. Various factors related to thermal comfort

Understanding thermal comfort in healthcare facilities is complex and multifaceted, involving a combination of physical, physiological, and behavioral factors. These factors can be broadly categorized under rational and adaptive thermal comfort approaches. The rational thermal comfort approach primarily focuses on six factors (air temperature, mean radiant temperature, air velocity, relative humidity, clothing thermal resistance, and metabolic rate). The adaptive approach considers how individuals adjust their behavior and expectations based on the surrounding environment, emphasizing the importance of personal control and adaptive actions to maintain comfort. Current research on thermal comfort in Chinese healthcare facilities has also researched various related factors, underscoring the complexity of achieving optimal indoor environments in healthcare settings.

The physical environmental factors significantly interacts with thermal comfort, Wang [54] investigated the interactive effects of combined acoustic, luminous, and thermal factors on human comfort in gynecologic oncology wards. The study compared the influence of different environmental factors on the comfort levels of both patients and caregivers. It revealed that higher thermal comfort of patients and caregivers corresponded to higher perceived luminance and acoustic comfort. Similarly, research by Wu et al. [87] confirmed these findings, indicating that acoustic perception is influenced by air temperature, with lower air temperatures improving participants' assessment of the acoustic environment. Additionally, the indoor environmental quality in healthcare facilities is critically important, as it directly affects the well-being of patients, staff, and visitors. Many aspects of indoor environmental quality are influenced by humidity levels. Dust mites and fungi proliferate at humidity levels above 65 %, while bacteria prefer below 30 %. To curb these pollutants, maintaining humidity between 30 % and 50 % is recommended. Furthermore, increasing ventilation can reduce pollutant concentrations, although it doesn't hinder growth [48]. Notably, indoor formaldehyde levels positively correlate with humidity ($r = 0.588$, sig. = 0.057), while radon levels negatively correlate during winter ($r = -0.891$, sig. = 0.017) [73], highlighting the importance of humidity management in maintaining IAQ. Zhang et al. [88] analyzed the impact of different ventilation strategies on outdoor air pollution control and indoor thermal comfort. Using experiments and computational simulations, they found that the side wall and returning on the side wall enhances indoor climate and thermal comfort by 29–36 %.

Physiological and behavioral factors also play a crucial role in

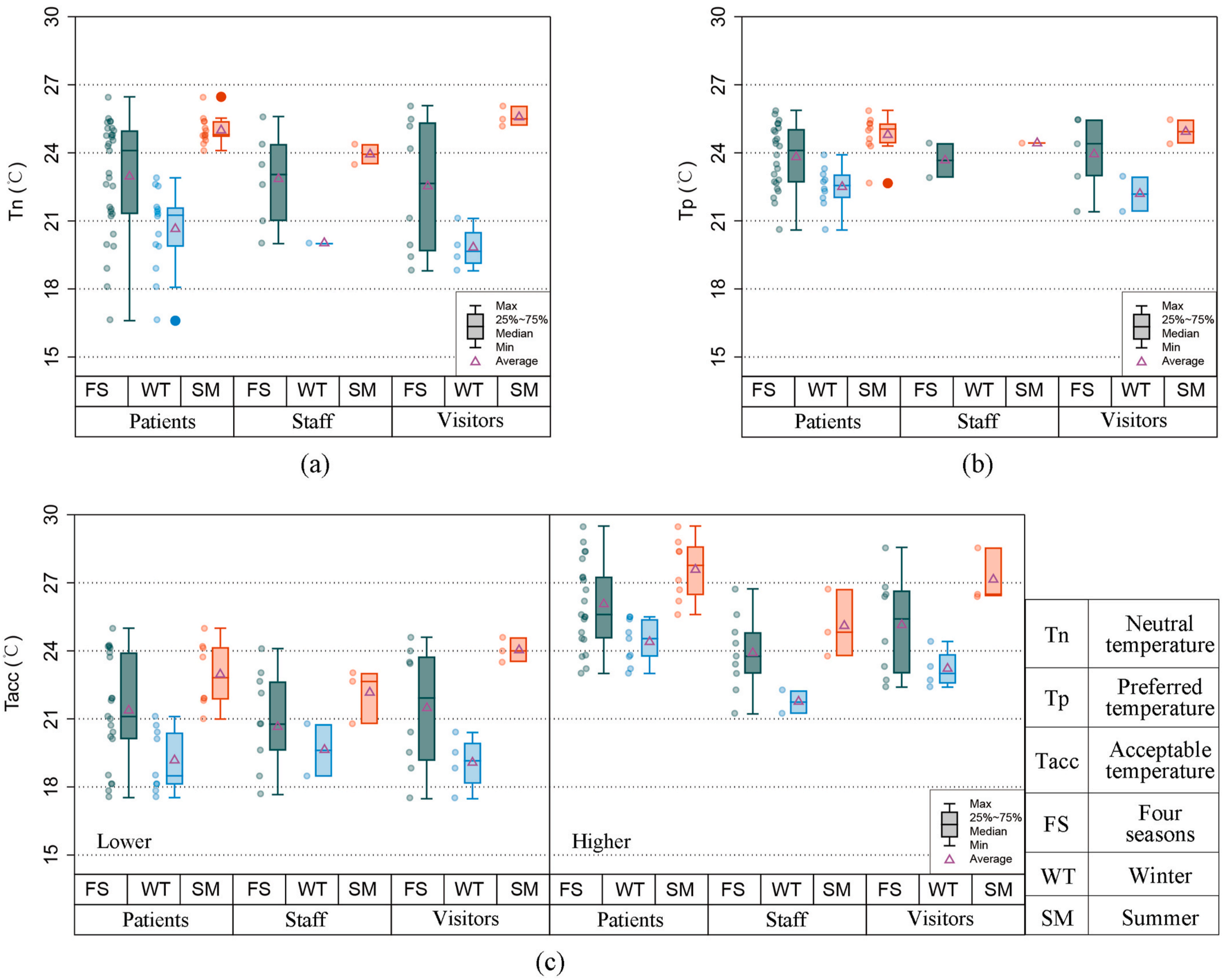

Fig. 5. Comparison of thermal environment and sensation between different demographic groups in healthcare buildings.

thermal comfort. Zhang [89] investigated the relationship between thermal comfort and health, finding correlations between thermal comfort and health indicators, influenced by exposure time. Skin temperature, especially on the forehead, strongly correlated with stress hormones (Cor and NE) and immune markers (S-IgA and S-IgE). Brain wave activity in the F8 channel correlated positively with Cor and NE, while FC5 and F8 channels had inverse relationships with S-IgA and S-IgE levels. Additionally, sympathetic nervous system changes negatively correlated with S-IgA and S-IgE levels. Total cardiovascular variability was positively associated with S-IgA but negatively with Cor, NE, and perceived stress, highlighting the complex relationship between thermal comfort and health. Wu et al. [87] identified that environmental comfort ranges differ based on health status, with "very weak" individuals preferring temperatures between 23.5 and 24.3 °C. Ji [59] found that using a metabolic rate of 1.2 met for pregnant women provides the most accurate prediction of their thermal sensation, underscoring the importance of considering individual metabolic rates in thermal comfort assessments. Zhang et al. [90] created equations and comfort charts for winter and summer, enabling the identification of thermally neutral environments for patients with varying metabolic rates. Du [91] explored the effect of temperature variation on human thermal regulation, health, and its molecular mechanism. The study revealed that individuals can autonomously adjust their physiological and behavioral responses to maintain thermal comfort within a temperature range of 10 °C–26 °C. This adaptation could reduce reliance on heating and air conditioning systems, thereby achieving a measure of energy conservation in buildings. Beyond this temperature range, the capacity for self-regulation diminishes, necessitating additional heating and cooling interventions to maintain indoor comfort and meet health requirements.

In addition, several scholars have developed adaptive thermal comfort models for patient thermal comfort under various parameter combinations. Yao et al. [92] explored how indoor thermal conditions and activity levels affect comfort inside disposable medical protective clothing (MDPC). The results showed indoor temperatures alter MDPC's internal temperature and humidity by around 1 °C and 10 %, respectively. The study proposed a model predicting internal conditions like work time, intensity, and temperature and humidity for different body areas under varied indoor temperatures. This research is notable for its consideration of adaptive parameters, specifically clothing. Gong et al. [50] developed an artificial neural network-based model to identify factors affecting patients' thermal comfort in healthcare settings, examining the impact of spatial and health-related variables on model accuracy. Spatial factors included the positioning of windows, doors, and air conditioning, as well as surface temperatures and orientations. In addition, health-related parameters included ambient environment, room orientation, biosignals, and ongoing medical treatments.

Table 6
Standards of healthcare facilities in China.

Standard	Functional areas	Precondition	Season	Temperature range (°C)
GB51039-2014, Code for design of general hospital [22]	Outpatient department	Consultation rooms, Examination rooms and Treatment rooms	WT	18.0–24.0
		Office or activity rooms	WT	18.0–20.0
		Outpatient waiting area and offices rooms	WT SM	≥18.0 ≤26.0
	Emergency department	Emergency department	WT SM	≥18.0 ≤26.0
	Inpatient department	Wards	WT SM	20.0–24.0 ≤27.0
		ICU	WT SM	≥24.0 ≤27.0
		Hematology ward	WT SM	≥22.0 ≤27.0
		Grade IV burn ward	FS	24.0–26.0
		Allergy asthma ward	FS	24.0–26.0
		Neonatal ward	FS	22.0–26.0
		NICU	FS	24.0–26.0
	Operating department	Operating rooms	WT SM	20.0–24.0 ≤27.0
		Delivery rooms	WT	20.0–24.0
	Medical technical department	Laboratory, pathology department, and various other laboratories	WT SM	≥22.0 ≤26.0
GB50333-2013, Architectural technical code for hospital clean operating department [84]	Operating department	Operating room	FS	21.0–25.0
		Cardiopulmonary bypass, preoperative area, nursing station, clean zone corridor, scrub room	FS	21.0–27.0
GB/T 18,883, Standards for indoor air quality [85]		Heating room air-conditioned room	WT SM	16.0–24.0 22.0–28.0
DBJ50-052-2013, Design standards on public building energy saving (green building) [86]		Heating room, I (High level of expectation)	WT	22.0–24.0
		Heating room, II (Normal level of expectation)		18.0–22.0
		Cooling room, I (High level of expectation)	SM	24.0–26.0
		Cooling room, II (Normal level of expectation)		26.0–28.0

4. Discussion

Healthcare facilities are among the most energy intensive of all public buildings and responsible for a substantial portion of total commercial energy consumption in China [93]. The demand for medical environments is escalating, with preferences shifting towards comfortable healthcare settings, advanced medical technologies, and sophisticated diagnostic and treatment equipment. This shift has led to an increase in energy consumption in healthcare facilities [94]. Notably, hospitals are considered to be among the least energy-efficient public structures [95,96]. In Chinese hospitals, the sources of energy consumption costs encompass electricity, steam, water, medical gases, and other utilities, with electricity being the most significant, constituting up to 64 % of the total. Hence, it is evident that electricity is critical within hospital operations, representing the most direct and effective method for energy conservation in healthcare facilities [3].

Reducing energy consumption necessitates maintaining acceptable levels of IEQ for occupants. It is widely recognized that the thermal environment plays a significant role in the indoor ambiance, influencing comfort, well-being, safety, and health outcomes for both patients and healthcare staff [97]. When HVAC systems are optimally selected and operated, energy savings of up to 30 % are achievable, all while maintaining a satisfactory thermal comfort level [98]. Sun et al. [42] performed an annual evaluation in a Zhejiang hospital, assessing satisfaction, indoor conditions, and energy use. They developed and validated a new energy-environment model for measuring energy efficiency and proposed a specific IEQ model for hospitals. Shi et al. [99] devised a multi-criteria decision-making framework to guide investors towards selecting the most advantageous renovation strategies for hospital wards, factoring in energy efficiency, economic viability, and thermal comfort. Gaspari et al. [100] explored the role of parametric design in the retrofitting of hospitals to enhance energy savings and comfort levels. Teke and Timur et al. [101] discussed the adoption of Variable Refrigerant Flow technology as an alternative to conventional HVAC systems, highlighting its potential for improved energy efficiency and cost savings.

The analysis reveals that in Chinese healthcare facilities, there are specialized zones and specific groups of people who have a wider tolerance for temperature differences than what is typically defined by comfort standards. This discrepancy suggests that the pre-set thermal conditions in healthcare facilities inadequately reflect the varied comfort needs of its occupants. By adjusting HVAC controls to cater to these specific preferences, healthcare facilities can achieve a mutual benefit. They can provide alignment with actual comfort needs while facilitating significant energy savings. This approach not only aims to optimize energy use by avoiding unnecessary heating or cooling but also indicates the necessity to revise existing thermal comfort standards. Incorporating these findings allows for the development of a more inclusive and adaptable thermal regulation framework in healthcare settings, promoting enhanced comfort for occupants and improved energy efficiency.

5. Conclusion

This study provides a comprehensive analysis of thermal comfort within Chinese healthcare environments, highlighting significant insights across different climatic zones, demographic groups, and various healthcare settings. Key findings and implications for future research and standard development include.

(1) Research is predominantly concentrated in the HSCW zone, indicating a critical need for expanded studies across China's diverse climatic regions to tailor thermal comfort solutions effectively. Despite comprehensive studies in the HSCW zone across various healthcare facilities and functional areas, there are notable gaps in other zones. Research in the C zone is limited to general hospitals and nursing homes, with a notable absence of research on other facility types, such as community hospitals. The HSWW zone is primarily explored in the context of general hospitals, leaving other essential healthcare facilities under-researched. In the SC zone, research is restricted to inpatient departments within general hospitals and nursing homes, ignoring other essential functional areas and healthcare facilities. The M zone has only one study, highlighting a notable gap in research on different categories of healthcare facilities and functional areas in different climatic zones.

(2) The construction of healthcare facilities of varying classes in China is influenced by factors such as policy and funding, leading to disparities in IEQ. Current literature highlights the multifaceted nature of thermal comfort, affected by elements like sound

and lighting. However, Class 3 A hospitals, which account for only 0.17 % of all healthcare institutions and 4.6 % of all hospitals in China, are predominantly the focus of existing research, with a noticeable gap in studies on hospitals of other classes (Class 2 A and 1 A) and primary healthcare facilities.

(3) While the inpatient department are well-studied, less emphasis has been placed on outpatient department, emergency department, operating department within healthcare facilities in China. When considering different categories of healthcare facilities, research is predominantly concentrated in Class 3 A general hospitals, whereas studies on Class 2 A hospitals and nursing homes mainly focus on inpatient departments. This gap highlights the importance of diversifying research efforts to include all functional areas of different categories of healthcare facilities.

(4) Although there is notable research on patients, investigations into the thermal comfort of staff and visitors are less comprehensive.

(5) The comparison of thermal sensations across different populations to existing standards reveals that while the standards generally meet broad thermal needs, they fall short in addressing the specific requirements of special populations and certain functional areas. This discrepancy points to the potential for refining current standards to better accommodate diverse thermal comfort needs, thereby enhancing design precision and contributing to energy conservation.

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CRediT authorship contribution statement

Rui Guan: Writing – original draft, Conceptualization. **Jun Lu:** Writing – review & editing, Methodology, Conceptualization. **Zhen Peng:** Formal analysis. **Siyu Ma:** Visualization. **Wu Deng:** Writing – review & editing. **Zhiang Zhang:** Writing – review & editing. **Paolo Beccarelli:** Writing – review & editing. **Tong He:** Writing – original draft.

Declaration of generative AI and AI-assisted technologies in the writing process

Statement: During the preparation of this work the authors used ChatGPT and DeepL Write in order to translate and embellish the paper. After using this tool, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2024.111927.

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