Localized thermal control for global impact: A meta-analytical review of thermal comfort and energy performance of personal comfort systems

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Abstract

Personal Comfort Systems (PCS) offer individualized thermal control that enhances occupant comfort, while reducing energy consumption in buildings. By enabling localized environmental adjustments without affecting other people, PCS present a promising strategy for energy-efficient building operation. Despite growing evidence of their benefits, a comprehensive synthesis of PCS performance, particularly regarding thermal comfort and energy outcomes, remains limited, hindering broader implementation. This meta-analysis evaluates 64 peer-reviewed studies to quantify the effectiveness of PCS. Findings indicate that PCS improve thermal sensation and overall comfort by an average of one scale unit. They also shift comfort temperature thresholds by 2.2°C, lower in heating and higher in cooling modes, allowing for expanded HVAC setpoint ranges and associated energy savings. PCS demonstrate stronger corrective effects on perceived ambient temperature under both high and low thermal conditions compared to those within the comfort zone, with an average corrective energy power of 42.6 W/°C. Among heat transfer methods, conduction and hybrid approaches outperform others in both heating and cooling, while convection is found particularly effective in cooling scenarios. The study develops the Coefficient of Comfort Temperature Shift (*CCTS*), a metric for

evaluating the performance of PCS in modifying comfort temperature thresholds. This metric supports HVAC setpoint optimization and offers practical pathways for energy savings. Overall, the findings position PCS as a viable solution for enhancing occupant comfort and reducing energy demand through individualized thermal control. By enabling precise microclimate adjustments, PCS contribute to sustainable building practices and occupant well-being, supporting global efforts toward energy-efficient built environments.

Keywords: Personal comfort systems, Meta-analysis, Thermal sensation, Thermal comfort, Comfort temperature, Energy savings

Nomenclature

PCS : Personal comfort systems

TSV : Thermal sensation vote

OC : Overall comfort

T_c : Comfort temperature (°C)

T_{in} : Indoor air temperature (°C)

CP : Corrective power (°C)

CEP : Corrective energy power (W/°C)

1. Introduction

1.1. Overview

Personal Comfort Systems (PCS) are gaining popularity as a sustainable solution to lower the overall building energy consumption while improving individual thermal comfort. Currently, buildings consume up to 40% of global energy, with nearly half of this energy demand attributed to space heating or cooling [1–3]. Heating, ventilation and air conditioning (HVAC) systems are estimated to meet 80% of occupants' comfort requirements [4,5]. Integrating PCS is likely to further improve thermal satisfaction and reduce the overall energy use of the building. Studies have shown that PCS can lower HVAC energy consumption between 4–60% [6–8] and achieve overall energy savings of 32–73% through targeted conditioning and adjustments to room temperature setpoints [9–12]. By providing localized heating or cooling, PCS enhance individual comfort without requiring changes to the room temperature. This dual benefit of overall energy efficiency and personalized thermal regulation [10] is aligned with future energy conservation goals. Despite the growing body of research on PCS, a significant research gap remains in comprehensively evaluating and synthesizing their overall impacts across diverse contexts and parameters. This gap has hindered widespread global adoption of PCS. Several challenges contribute to this limited uptake. Many buildings lack the necessary infrastructure, also centralized heating systems restrict individual control [13]. Social norms favor uniform heating, making personalized systems less acceptable [12]. Additionally, current PCS technologies frequently suffer from limited functionality and usability; and users often lack the knowledge to operate and optimize these systems [13,14]. Overcoming these barriers requires coordinated efforts from industry and policymakers to establish standards, provide incentives, and promote end user education.

1.2. Indoor comfort, PCS and Assessments

Indoor thermal comfort plays a vital role in occupant health, satisfaction, and productivity, as people spend 80 to 90% of their time indoors [15,16]. Thermal comfort is shaped by a combination of personal and environmental factors, including air temperature, radiant temperature, relative humidity, air velocity, clothing insulation, and metabolic rate. Deviations from the thermal comfort status of the occupant is shown to negatively impact their physiological, psychological, and cognitive status [15–19]. Conventional HVAC systems aim to maintain uniform thermal conditions across entire spaces, often overlooking individual preferences and microclimatic variations. PCS are especially beneficial in shared or open-plan spaces, where centralized systems often struggle to meet diverse comfort requirements. By allowing fine-grained control over personal heating and cooling, PCS reduce reliance on whole-room conditioning and support more adaptive comfort strategies. Also, the internal thermal environment of some buildings does not meet the basic thermal comfort requirements, due to fuel poverty and other reasons. In such cases, PCS can provide localized thermal comfort. PCS target body parts with different thermal sensitivities, mainly in three categories, including wearables (e.g. thermal garments), portable (e.g. portable air conditioners and foot warmers), and fixed PCS (e.g. thermal table, ceiling fans) [20]. PCS enable occupants to feel more comfortable, while being exposed to a wider range of indoor thermal conditions [10,21]. The individualized user control aspect of PCS enhances thermal acceptability up to 96% and satisfaction up to 99% [22,23]. This dual advantage of personalized comfort and reduced energy use positions PCS as a key element in sustainable building design.

The most commonly used method of assessing the immediate thermal comfort status is a subjective Thermal Sensation Vote (TSV). This is a 7-point Likert scale from cold to hot with the desired response set in the middle, as neutral [24–29]. Another commonly used method is the Overall Comfort (OC) level, which indicates a holistic evaluation incorporating thermal and non-thermal comfort aspects [29]. The comfort temperature (T_c) refers to thermal conditions that occupants find most comfortable. Also, T_c is the key measure in setting the boundaries of comfort zone. Previous studies revealed substantial global variations in T_c between 15 to 33.8°C [30]. This range was found between 14 to 32°C in naturally ventilated environments [31], highlighting the significance of contextual adaptation in thermal comfort. Also, moderately elevated temperatures in conditioned spaces are shown to enhance comfort and health conditions [32]. The individual's thermal perception and comfort temperature are affected by various environmental, technical and personal factors, such as ethnicity, cultural background, and anthropometric characteristics [33,34]. Even though there are numerous PCS studies conducted in diverse contexts, there is a lack of a holistic assessment of the impact of PCS on thermal perception and thermal comfort boundaries. Thus, the overall impact of PCS is underestimated regardless of environmental, personal and system factors.

1.3. Performance and energy savings

PCS technologies contribute to energy savings by directly heating or cooling the individual, rather than the entire building. Although PCS devices were not initially designed for energy efficiency, they reduce reliance on traditional HVAC systems and support more sustainable building operations [20–22]. Also, boarder range of acceptable indoor temperatures allows for more relaxed HVAC setpoints, leading to substantial energy savings. For example, relaxing the setpoint of thermostat by just 1°C for both heating and cooling has shown to save 10% of the total energy use of the building [35,36]. Field studies further demonstrate that raising cooling setpoints in air-conditioned buildings yields 19-40% energy savings, while maintaining occupant comfort potentially reaching up to 70% in total savings [37]. Similarly, Arens et al. [38] and Zhang et al. [39] found that adjusting setpoints by +2°C (cooling) and -2.5°C (heating) while using the PCS technologies reduces HVAC energy use by 25-40% without compromising thermal comfort. Also, PCS consume significantly less energy per occupant compared to conventional HVAC systems. Most PCS devices require only around 1% of the energy demand of centralized HVAC systems [12], as they heat or cool the individual directly, rather than space heating or cooling, which is much more energy intensive [36]. For instance, PCS chairs consume a maximum of 0.96kWh, whereas conventional HVAC systems require an average of 30 to 42kWh per occupant during occupied hours [21,22].

To evaluate PCS performance and energy efficiency, two metrics have been introduced: Corrective Power (*CP*) and Corrective Energy Power (*CEP*)[40,41]. *CP* quantifies the effectiveness of PCS, as it measures how much a PCS can "correct" the ambient temperature towards thermal neutrality, while *CEP* assesses the energy efficiency of PCS devices relative to their comfort-improving capabilities. *CP* represents the temperature difference between two ambient conditions that produce the same thermal sensation: one with PCS and one without [41,42]. For instance, *CP* is the difference in the indoor air temperatures, when a heated mat is used versus when it is not, while the user's thermal sensation remains neutral.

CEP links *CP* to the device's energy use, enabling comparisons across different PCS technologies based on their efficiency in providing thermal comfort [41]. These metrics are essential for evaluating and comparing various types of PCS. Several studies have applied cross comparison of PCS devices using *CP, such as* Zhang et al. [41], Tang et al. [43] and Song et al. [36]. However, inconsistencies in environmental, personal and system factors as well as in the assessment of PCS technologies across studies. Some studies totally lack the use of any measures to examine the energy performance of PCS. This contributes to a fragmented understanding of PCS energy performance globally, regardless of contextual variables. Although most research agrees on the comfort and energy-saving potential of PCS, widespread adoption requires a deeper understanding of how thermal perception, comfort boundaries, and energy performance interact across diverse settings.

1.4. Research gap and objectives

PCS have been studied across a wide range of climatic contexts globally, resulting in a diverse body of research encompassing varied populations, environmental conditions, PCS technologies, and methodological approaches. However, this heterogeneity presents challenges in isolating and quantifying the precise impact of PCS on thermal comfort and energy performance. Key thermal perception metrics, including *TSV* and *OC*, are critical for evaluating PCS effectiveness, while *Tc* serves as a boundary metric that reflects shifts in thermal preference under the influence of PCS. These parameters are directly linked to thermostat settings, thereby influencing HVAC operation and the potential for energy conservation. In addition, *CP* and *CEP* are critical for assessing the capacity of PCS to modify the thermal environment and their associated energy demands. Although several reviews and meta-analyses have explored the energy and comfort benefits of PCS [23,34–36,41,44,45], they often focus on isolated aspects. A comprehensive understanding of PCS, including their influence on thermal perception, comfort boundaries, and energy performance across both heating and cooling modes, remains underexplored.

Addressing these research gaps could significantly enhance the adoption and optimization of PCS technologies for broader applications, potentially leading to more energy-efficient and comfortable built environments. Figure 1 illustrates the research gap and proposes an analytical framework for this study to address the research gap. The central section of the framework highlights the effects of PCS on thermal perception, thermal comfort boundaries, power, and energy use. The left side outlines information related to PCS setup, while the right side shows the specific metrics involved in the performance assessment. The top segment shows the key factors influencing PCS performance. As shown in Figure 1, the literature reveals a significant gap in comprehensively evaluating the overall performance of PCS across individual parameters, particularly when synthesizing findings from diverse studies.

This study aims to systematically evaluate the comfort and energy performance of PCS under both heating and cooling conditions through a meta-analysis, using the following metrics:

- Improvement of thermal comfort perception using *TSV* and *OC.*
- Expansion of thermal comfort boundaries using T_c.
- Power and energy consumption using *CP* and *CEP*.
- Development of Coefficient of Comfort Temperature Shift (*CCTS*), a novel metric for quantifying PCS performance in shifting comfort temperature thresholds.

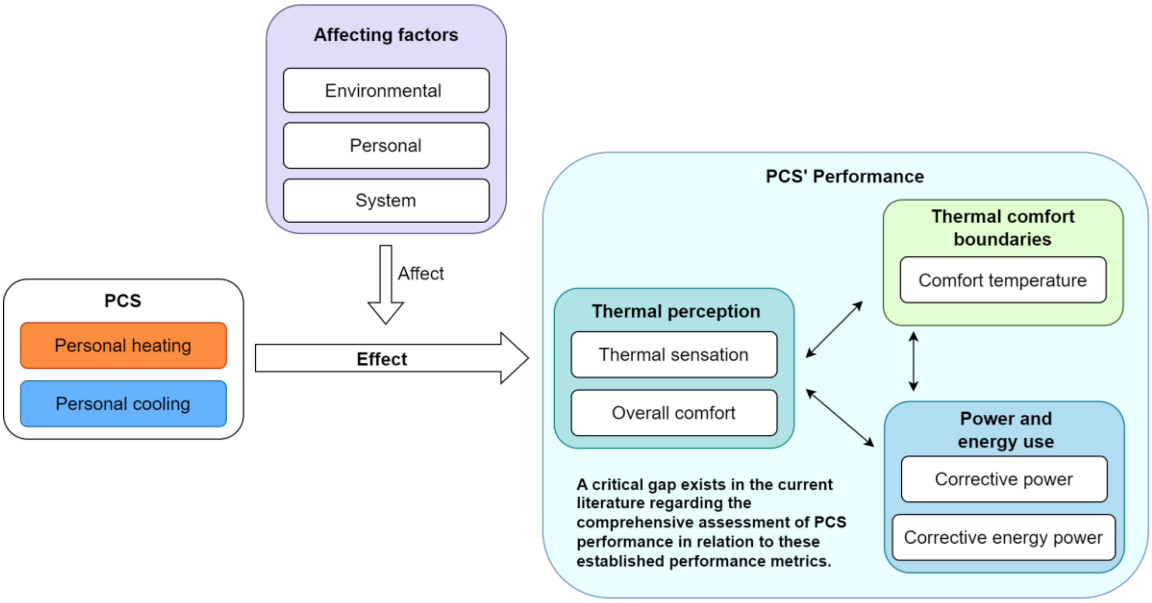

Figure 1. Research gap and analytical framework of this study.

2. Methods

This systematic meta-analysis adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [46], which provided a structured approach to enhance the review quality [47]. As demonstrated in Figure 2, PRISMA includes a checklist and a flow chart outlining a standardized three-stage process: identification, screening, and inclusion for the systematic selection and evaluation of sources for review. This framework is commonly used for assessing interventions [46], such as PCS, which aim to enhance occupant thermal comfort.

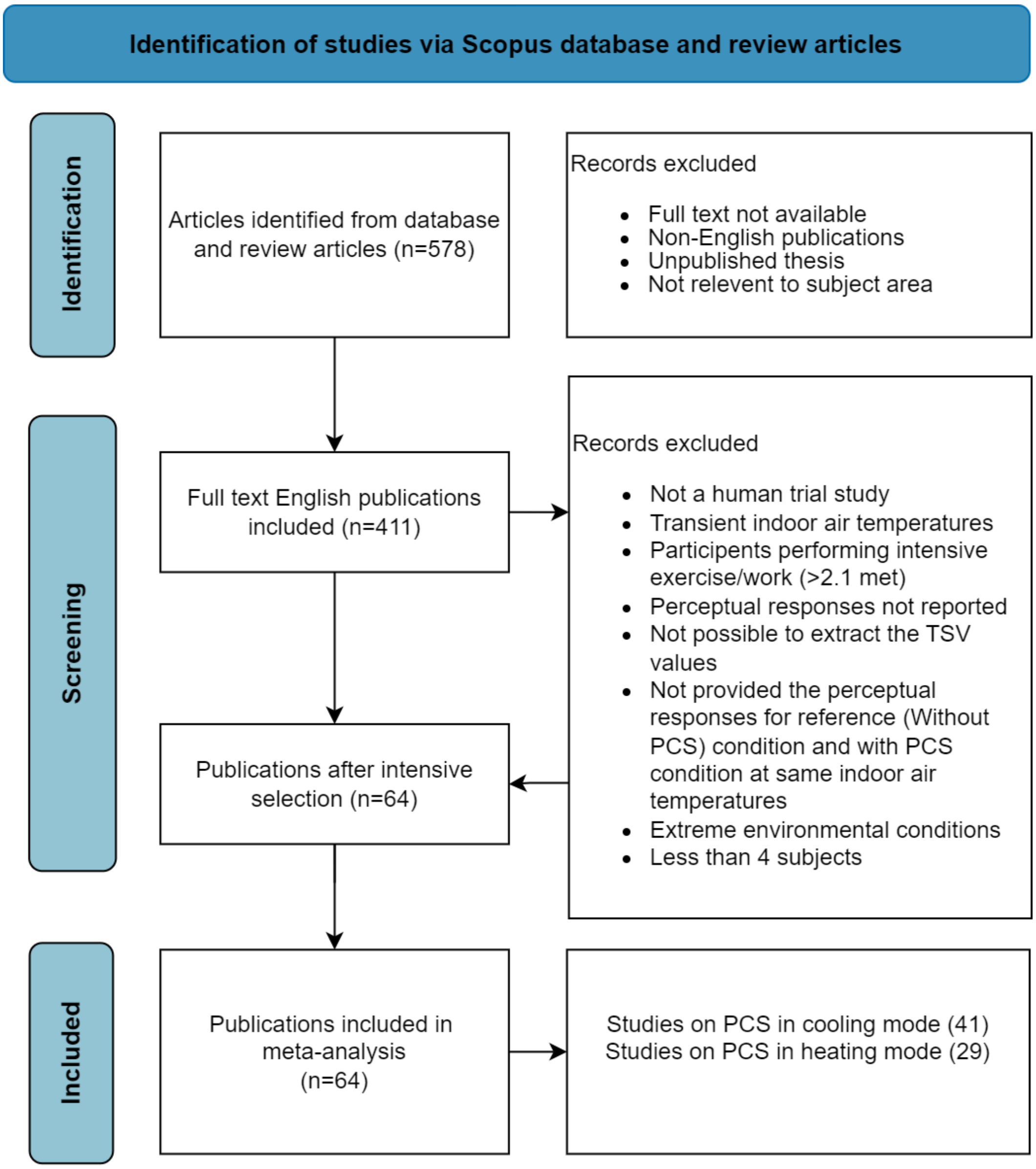

Figure 2. Preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram for the identification of the studies via database and review articles

2.1. Literature research

A comprehensive literature search was conducted using the Scopus database to identify studies related to PCS and occupant thermal responses in both heating and cooling modes. The search string used was: "personal AND comfort AND system OR device AND sensation OR subject". In addition, relevant studies cited in high quality PCS reviews [10,23,35,36,44,45] were also included.

2.2. Selection criteria

An extensive literature search yielded a large number of potential publications. The selection process is illustrated in Figure 2. Initially, studies not published in English, as well as those consisting only of abstracts or unpublished theses, were excluded. The remaining publications were screened based on the following inclusion criteria, aligned with the study objectives:

1. PCS had to be implemented in indoor environments, where participants were sitting, standing, or engaged in low-intensity activities (i.e. metabolic rate < 2.1 met).

2. PCS was required to be used for heating or cooling in environments with high (Generally >25°C) or low (Generally <23°C) indoor air temperatures, with the primary aim of achieving thermal comfort, as illustrated in Figure 5.

3. Studies had to be randomized controlled trials, where participants were assigned to either cooling/heating interventions or control trials.

4. Human trials were conducted in laboratory settings under steady-state thermal conditions or low transient field studies.

5. Studies had to report participants' overall perceptual responses (e.g. TSV, OC and thermal acceptability) using widely accepted subjective judgment scales based on body thermal state.

6. Studies had to include more than four participants.

7. Overall perceptual responses were provided for both with and without PCS conditions at the same indoor air temperature in graphs using a numerical form or scale.

From an initial pool of 578 articles, 167 were excluded during the identification stage and 347 during screening. As explained in Figure 2, a total of 64 articles were selected for inclusion in this meta-analysis, including 41 related to cooling mode and 23 related to heating mode. Across these studies, 476 TSV data points were extracted for with and without PCS conditions under identical indoor air temperatures.

2.3. Scale normalization

Various comfort measurement scales were used across the selected studies, including bipolar seven-point scales, bipolar continuous scales, unipolar numeric scales, and unipolar verbal scales. While no significant differences in sensitivity was reported when assessing physical factors [48], their reliability and the way respondents perceive and express thermal comfort can vary significantly [49] depending on the semantic meaning of scale points [48,50]. This semantic variability influences how participants interpret and report their thermal comfort. To address this in this review, the semantic meanings of comfort scales were considered in the normalization process. Previous meta-analyses by Humphreys [51] and Humphreys et al. [52] employed similar normalized to account for scale variation, particularly when studies did not uniformly use a 7-point scale. In the reviewed studies, all used the ASHRAE 7-point scale to assess *TSV,* but various scales were employed to assess OC, including 4-point, 5-point, 7-point, and 10-point scales [43,53,54]. To ensure consistency and comparability, all *OC* values were normalized to a 7-point scale, as adopted in numerous previous studies, as demonstrated in Figure 3. Examples of original scales included:

- -4 (Very uncomfortable) to 0 (Comfortable)
- -3 (Very uncomfortable) to 3 (Very comfortable)
- -3 (Very uncomfortable) to 0 (Comfortable)

- -2 (Very uncomfortable) to 2 (Very comfortable)

To normalize these scales, equivalent semantic values were mapped to the 7-point scale. For instance, in the -3 to 0 scale, -3 (Very uncomfortable) was mapped to -3, -2 (Uncomfortable) to -2, and -1 (Slightly uncomfortable) to -1. The range between -1 and 0 was adjusted accordingly, with 0 (Comfortable) aligned to the neutral point on the 7-point scale, ensuring consistency across all datasets.

Table 1. *TSV* and *OC* semantics scale for normalization

Scale	Thermal sensation vote *(TSV)*		Overall comfort (*OC*)	
	Normalized	**Used terms**	**Normalized**	**Used terms**
3	Hot	Hot	Very comfortable	Very acceptable, Clearly comfortable
2	Warm	Warm	Comfortable	Moderately comfortable
1	Slightly warm	Comfortably warm, A little bit warm	Slightly comfortable	Slightly comfortable
0	Neutral	No feeling, Comfortable	Neutral	No feeling, Just comfortable, Just uncomfortable, Not uncomfortable, Just acceptable, Just unacceptable
-1	Slightly cool	Comfortably cool, A little bit cold	Slightly uncomfortable	Slightly discomfort
-2	Cool	Cool	Uncomfortable	Discomfort, Moderately uncomfortable
-3	Cold	Cold	Very uncomfortable	Not acceptable, Very discomfort, Clearly uncomfortable

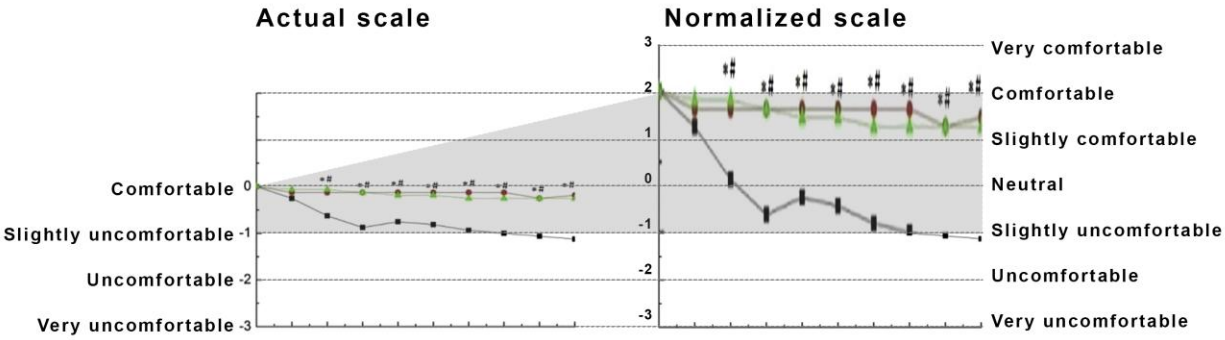

Figure 3. Original and normalized overall comfort scale

2.4. Data generation

PCS operation modes and heat transfer mechanisms are classified according to Song et al. [36], including: conductive, convective and radiative PCS. Conductive devices are directly in contact with the skin, while convective devices are positioned slightly away from the body part and rely on altering the immediate air temperature. Radiative PCS deliver heat through radiation directed at the body part without requiring direct contact or changes to the surrounding temperature.

To assess the impact of PCS, parameter values were collected under both with and without PCS conditions at the same indoor air temperature, with the condition without PCS serving as the reference. The lowest effective PCS condition was assumed to represent the absence of PCS, such as the fan speed approaching zero [53]. In case the study reported data only during PCS operation (i.e. not including conditions, when PCS was not in use), TSV and OC values at the experiment's starting point (t = 0) (55–58) or prior to PCS activation [59] were used as reference conditions. Mean *TSV* or OC values for PCS conditions were calculated after a 20-minute adaptation period to ensure steady-state thermal conditions [60]. In cases where both PCS conditions were not examined within the same survey period [20], data from adjacent months or the nearest available survey dates were used. In studies with fluctuating environmental conditions, average indoor air temperatures were considered [61,62]. In all referenced studies, air temperature was measured for indoor temperature. In cases where the climate type was not explicitly reported, it was inferred from the study location using the Köppen climate classification system [63,64]. Data points were extracted using LabPlot software [65] to ensure precision. When OC values were not explicitly reported, overall thermal acceptability scores were used as proxies due to their strong correlation with OC [66]. Additionally, when OC values were only available through graphical representations (e.g., OC vs. TSV plots), corresponding OC values were estimated from the graphs [60].

When the metabolic rate was not reported in the study, it was predicted following previous studies based on the activities they have mentioned

(67–69). When the clothing insulation (I_{cl}) value was not provided in the study, but descriptions of the subjects' clothing were available, the I_{cl} value was estimated according to the description (70). However, estimating I_{cl} was occasionally challenging, due to additional cooling or ventilation effects from the equipment (71).

To avoid skewing the results, studies employing high-power-consuming devices (e.g., 5090 W) were excluded from the analysis (72). When only a range of power consumption values was provided—along with adjustable temperature (73) or speed settings (74), power values were estimated based on temperature variation, assuming a linear operational relationship.

2.5. Calculations

T_c was calculated for all TSV values using the Griffiths' equation.

$$T_c = T_{in} + (0\text{-}TSV)/a \tag{1}$$

Where T_c represents comfort temperature (°C), T_{in} is indoor air temperature (°C), *TSV* is the thermal sensation vote, and *a* is the Griffiths constant. A Griffiths' constant of 0.33 was utilized, aligned with Fanger [75] because more than 80% of the experiments of the referred studies conducted in climate chambers or semi control environment. Furthermore, the value of *1/a* has been observed to range between 2 and 6 °C per Likert scale unit [76], influenced by factors such as the type of occupancy and the extent of body coverage achieved by the PCS. Previous studies confirmed that thermal sensitivity is higher in air conditioned spaces (a = 0.44~0.47 sensation units per °C) compared to naturally ventilated buildings (a = 0.21~0.22 sensation units per °C) [77,78]. Field studies in China has found 0.26~0.32 sensation units per °C variations in sensitivity [79]. Most of the included studies for this meta-analysis are from China. Considering all these facts, this study, chose a mid-range value of 3.0 °C per scale unit (a = 0.33 sensation units per °C) (76) of the temperature range specified by ASHRAE and ISO comfort zones, which span one scale unit and equate to approximately 3 °C [80].

For this study, Corrective Power (CP, °C) is defined as the difference between two indoor temperatures that result in the same thermal sensation, one without the PCS and one with the PCS in operation [38]. CP exhibits negative values in cooling mode and positive values in heating mode, reflecting a decrease or increase in perceived ambient temperature due to PCS, respectively. These opposing values may lead to confusion when evaluating PCS performance. To address this issue, the absolute values of CP were considered in this study. The absolute difference of TSV values in the same temperature used to obtain the $|CP|$ as expressed below:

$$|CP| = |TSV_{With\ PCS} - TSV_{Without\ PCS}|/a \quad (2)$$

Here, $TSV_{With\ PCS}$ and $TSV_{Without\ PCS}$ refers to the thermal sensation reported with and without PCS, and a is Griffiths' constant.

Corrective Energy Power (CEP, W/°C) is utilized to evaluate PCS's energy efficiency in achieving thermal comfort for occupants. It is defined as the quantification of how effectively a particular heating or cooling system can adjust an individual's thermal sensation from a state of discomfort to a comfortable one, typically expressed in terms of temperature difference. The CEP index is determined by comparing the corrective power required to maintain comfort against the system's energy consumption (81,82). Absolute

CEP was utilized to ensure clarity similar to CP and calculated using the following equation:

$$|CEP| = \text{Power of the device}/|CP| \tag{3}$$

The Coefficient of Comfort Temperature Shift ($CCTS$) is introduced in this study to quantify the effect of PCS from the perspective of comfort temperature. This coefficient is calculated to assess the impact of PCS on T_c in various studies, ensuring that the power of the device is represented without positive or negative values. The $CCTS$ is calculated using the following equation:

$$CCTS = T_{c\ with\ PCS}/T_{c\ without\ PCS} \tag{4}$$

3. Results and discussion

This section begins by introducing the environmental, personal, and system factors influencing PCS performance. It then discusses the effects of PCS on thermal perception, followed by an analysis of PCS impact on comfort boundaries and energy performance. A new metric of CCTS is introduced to evaluate PCS performance in relation to occupant comfort temperature. The section concludes with a discussion of limitations and practical implications, along with suggestions for future research.

3.1. Nature of previous studies

Luo et al. [34] identified three key factors influencing PCS effectiveness: environmental, user related, and system specific. Table A1 and Figure 4 summarize the basic environmental, personal, and system characteristics of the 64 studies included in this meta-analysis. These studies were conducted across various countries with the majority originated from China (52%), followed by the USA (16%), Japan (8%) and the Netherlands (8%). This geographic distribution suggests a potential regional bias, particularly toward East Asian contexts, which may influence the generalizability of the findings to other climatic and cultural settings. Only 17% of the research was field studies, while the majority were conducted in climate chambers (i.e. 77%) and semi controlled-field environments (i.e. 6%). Although climate chambers offer controlled conditions ideal for isolating variables, they may not fully capture the complexity of occupant behavior, adaptive opportunities, and environmental variability present in real-world buildings. This overrepresentation of laboratory-based studies may limit the applicability of results to real-world settings, particularly in naturally ventilated or mixed-mode buildings [83]. Most studies simulated indoor office environments involving light desk bound activities. A wide range of PCS devices were employed; and environmental and personal factors varied across the studies, as shown in Table 2. 41 studies focused on cooling and 29 focused on heating mode. Regarding the sample size, 33% of the studies involved between 16 and 20 respondents, while 50% included 16 or fewer participants.

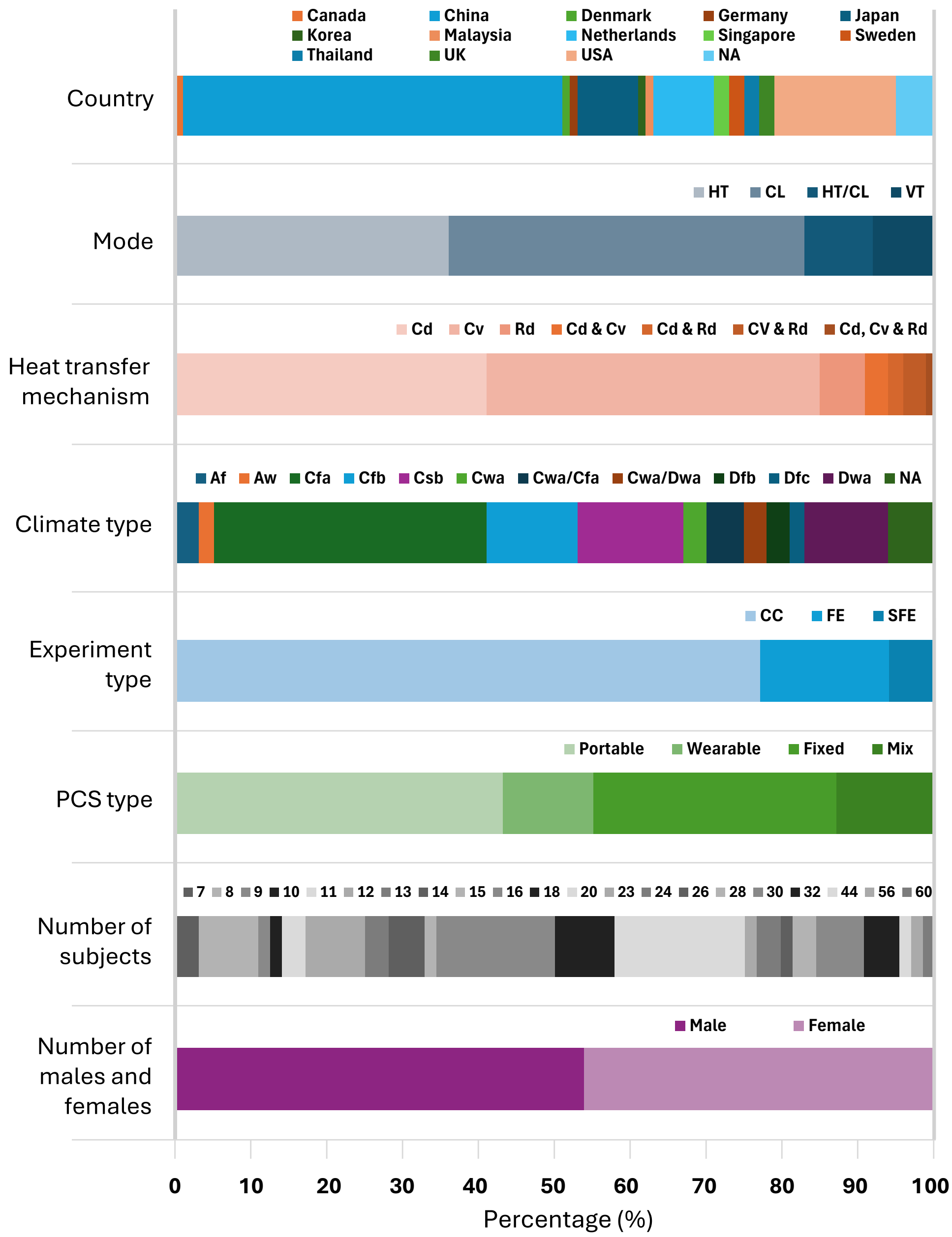

Figure 4. Percentages of each aspect of PCS studies (NA: Not available, CD: Conduction, CV: Convection, RD: Radiation, Cl: Cooling, HT: Heating, VT: Ventilation, CC: Climate chamber, FE: Field experiment, SFE: Semi field experiments (conducted in real world conditions but controlled environments), Mix: Mixed types applied simultaneously)

Additionally, experiments have been conducted across a range of climate types, such as Cfa (36%), followed by Csb (14%), Cfb (12%), and Dwa (11%). According to Exss et al. [23], There were 43% of portable, 32% of fixed, and 12% of wearable devices employed in included studies. 13% of studies incorporated mixed device types, such as combinations of wearable and portable devices or fixed with portable technologies.

In 99% of the reviewed studies, the indoor air temperature remained consistent between conditions with and without PCS technologies. For heating mode, the reported temperature range was 5–26 °C, while for cooling mode, it ranged from 20–38 °C. Descriptive analysis indicates that the mean indoor air temperature during cooling mode was higher (28.7 °C) compared to heating mode (14.7 °C). Additionally, temperature variability was lower under cooling conditions, as illustrated in Figure 5.

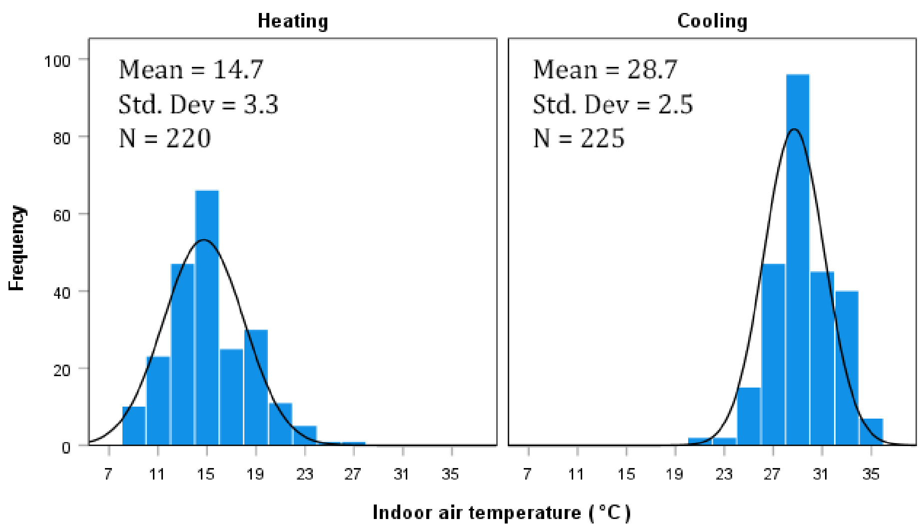

Figure 5. Distributions of air temperature for heating and cooling modes

In most studies, air velocity was maintained below 0.1 m/s in both heating and cooling modes. However, for cooling mode, air velocities ranged from 0.1 to 2.3 m/s, while for heating mode, they were generally kept below 0.3 m/s. The mean relative humidity was 50%, which is aligned with the baseline of most thermal comfort studies in controlled climate chambers [84]. Mean clothing insulation for heating and cooling modes were 1.15 clo and 0.53 clo, respectively. The metabolic rate for most studies was 1.0 met and 1.1 met. The most commonly used heat transfer mechanism in heating mode was conduction, typically involving contact-based devices such as thermal chairs, heating pads, and foot warmers. In contrast, convection was the dominant mechanism in cooling mode, primarily involving devices that influence airflow, such as fans.

3.2. Effect on thermal perception

Perceptual responses are essential for evaluating PCS, as they directly reflect user satisfaction and comfort levels. Subjective feedback has been shown to significantly correlate with PCS usage rates, thermal environment evaluations, and workplace productivity [85]. PCS enable comfort across a wider range of indoor temperatures by allowing individual adjustments, highlighting the importance of personal perception in system effectiveness. Notably, individual differences in thermal comfort are closely linked to perceived productivity in office settings [86]. Subjective comfort metrics are often more effective than physical parameters alone, as demonstrated by low correlation coefficients between PMV and subjective thermal metrics [87]. *TSV* is a key indicator of thermal comfort, capturing how individuals perceive their thermal environment [88]. *OC* reflects the combined effects of overall thermal environment offering a more comprehensive measure of comfort [87].

Figure 6 presents the mean *TSV* and *OC* values under with and without PCS conditions. The mean *TSV* with PCS is significantly higher than that without PCS in heating mode, and significantly lower than that without PCS condition in cooling mode. Similarly, the mean

OC with PCS is significantly higher than without PCS in both heating and cooling modes. The results indicate that PCS significantly enhance thermal comfort by shifting both *TSV* and OC by approximately one scale unit in both heating and cooling modes.

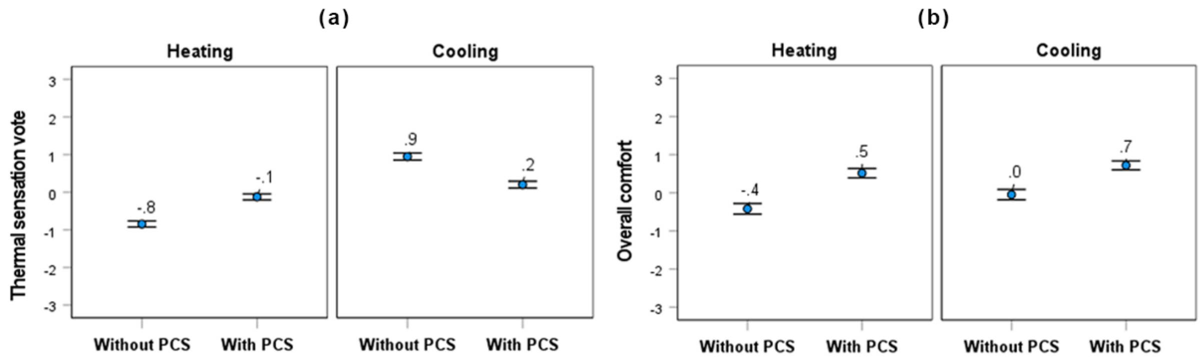

Figure 6. Mean and 95% confidence interval (mean ± 2S.E.) for with and without PCS: (a) Thermal sensation vote and (b) Overall comfort

Figure 7.a presents the relationship between thermal responses and indoor air temperature for the overall data with and without PCS conditions.

The TSV is positively correlated with indoor air temperature for both with and without PCS conditions. The following linear equations were found from regression analysis.

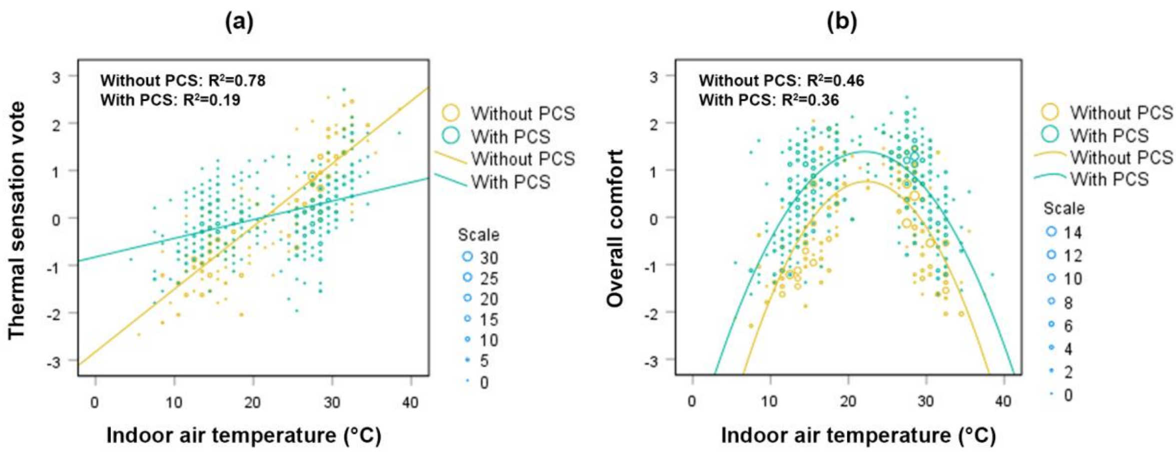

Figure 7. Relationship between thermal responses and indoor air temperature for with and without PCS conditions: (a) Thermal sensation and (b) Overall comfort.

Without PCS: $TSV = 0.13\ T_{in} - 2.82$ (N = 475, $R^2 = 0.78$, S.E. = 0.076, $p < 0.001$) (5)

With PCS: $TSV = 0.04\ T_{in} - 0.82$ (N = 475, $R^2 = 0.19$, S.E. = 0.089, $p < 0.001$) (6)

T_{in}: Indoor air temperature (°C), N: Number of cases, S.E.: Standard error of regression coefficient, p: Significance level of regression coefficients

The higher R^2 value for the case without PCS suggests a stronger linear relationship between TSV and T_{in} than when the PCS is used. The regression coefficient is lower in the with PCS than in the condition without PCS. This suggests that the PCS moderates the impact of indoor temperature on individual thermal comfort. When the indoor temperature is 15 °C, the improvement of TSV is 0.6 points and at 32 °C it is 1.0-point.

Figure 7.b shows the quadratic relationship between overall comfort and indoor air temperature for with and without PCS conditions. This indicates that comfort levels tend to increase with rising T_{in} up to a certain point, after which further increases in T_{in} lead to a decline in comfort. With PCS, data points appear higher than those without PCS condition data across the temperature spectrum, implying that using PCS improves overall comfort at any given indoor air temperature. The following quadratic equations were found from the regression analysis:

Without PCS: $OC = -0.016\ T_{in}^2 + 0.725\ T_{in} - 7.36$ (7)

(N = 431, $R^2 = 0.46$, S.E.$_1$ = 0.001, S.E.$_2$ = 0.039, $p < 0.001$)

With PCS: $OC = -0.013\ T_{in}^2 + 0.560\ T_{in} - 4.81$ (8)

(N = 431, $R^2 = 0.36$, S.E.$_1$ = 0.001, S.E.$_2$ = 0.037, $p < 0.001$)

S.E.$_1$: Standard error of the regression coefficient for T_{in}^2, S.E.$_2$: Standard error of the regression coefficient for T_{in}

While the R^2 value is slightly lower for with PCS compared to without PCS condition, both indicate a moderate fit of the quadratic model to the data. When the indoor air temperature in 15 °C, the improvement in *OC* is 1.0-point and in 32 °C, it is 0.9-points.

For both TSV and OC, the model fit in with PCS conditions showed relatively low values, indicating greater variability in perceived thermal sensation and comfort when PCS are used. This may be attributed to individual differences in personal factors as well as technical variations in the PCS such as targeted body parts, heat transfer mechanism, and power of the device used in the experiments [33,34,89].

Both heating and cooling PCS, primarily alleviate thermal discomfort through physiological effects by locally modulating skin temperature, cardiovascular responses, and metabolic activity while preserving overall thermoregulation [74,90–92]. While some studies have suggested that personal control over the thermal environment may lead to slight improvements in perceived comfort due to psychological effects [93], a recent study by Zierke et al. [94] found no significant impact of personal control on PCS. Instead, their findings indicate that thermal comfort is primarily influenced by appropriate thermal settings. These findings indicate that PCS can significantly improve the *TSV* and *OC* towards comfort in both heating and cooling modes.

3.3. Improvement of comfort temperature by PCS

Maintaining appropriate thermal conditions is essential for occupant health, well-being, and productivity. Designing energy-efficient buildings that account for thermal comfort contributes to overall satisfaction and performance while reducing energy consumption [30]. PSC that target extremities can stimulate thermoregulation responses during temperature fluctuations [54]. Therefore, understanding the comfort temperature under with and without PCS conditions is critical for achieving both energy savings and occupant comfort. To evaluate the impact of PCS on comfort temperature, Figure 8 presents the mean comfort temperatures under with and without PCS conditions. The results show that the mean comfort temperature with PCS is significantly lower than without PCS in heating mode, and significantly higher in cooling mode. This shift indicates that PCS can effectively expand the acceptable temperature range, thereby enabling relaxed HVAC setpoints. On average, PCS improved comfort temperature by approximately 1.5°C in both heating and cooling modes.

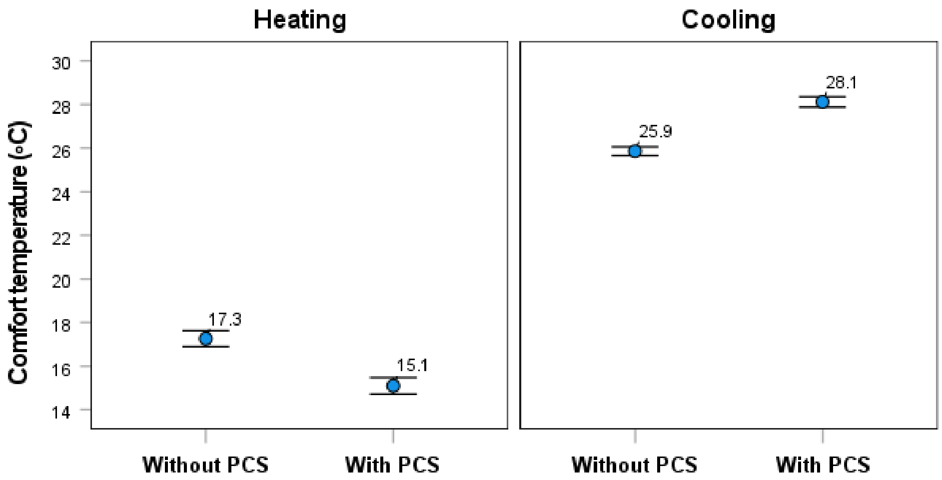

Figure 8. Mean comfort temperature and 95% confidence interval (mean ± 2 S.E.) with and without PCS

Understanding indoor comfort temperatures across a range of indoor temperature conditions for both heating and cooling modes is essential for optimizing energy efficiency, occupant comfort, productivity, and health in buildings, particularly in response to changing outdoor climates. To explore the relationship between comfort temperature and indoor air temperature by mode, scatter plots are presented in Figure 9. The analysis reveals a positive correlation: as indoor air temperature increases, comfort temperature also increases in both heating and cooling modes. Regression equations derived from this analysis quantify the relationship and provide a basis for predictive modeling in thermal comfort research.

Heating mode:

Without PCS $T_c = 0.69T_{in} + 7.1$ (N = 220, $R^2 = 0.70$, S.E. = 0.031, $p < 0.001$) (9)

With PCS $T_c = 0.72T_{in} + 4.5$ (N = 220, $R^2 = 0.71$, S.E. = 0.031, $p < 0.001$) (10)

Cooling mode:

Without PCS $T_c = 0.29T_{in} + 17.6$ (N = 255, $R^2 = 0.20$, S.E. = 0.037, $p < 0.001$) (11)

With PCS $T_c = 0.40T_{in} + 16.5$ (N = 255, $R^2 = 0.27$, S.E. = 0.042, $p < 0.001$) (12)

The high and similar R^2 values for both conditions indicate a strong linear dependence of comfort temperature on indoor air temperature, regardless of PCS use in heating mode, but in the cooling mode, the lower R^2 values indicate a weaker linear relationship between

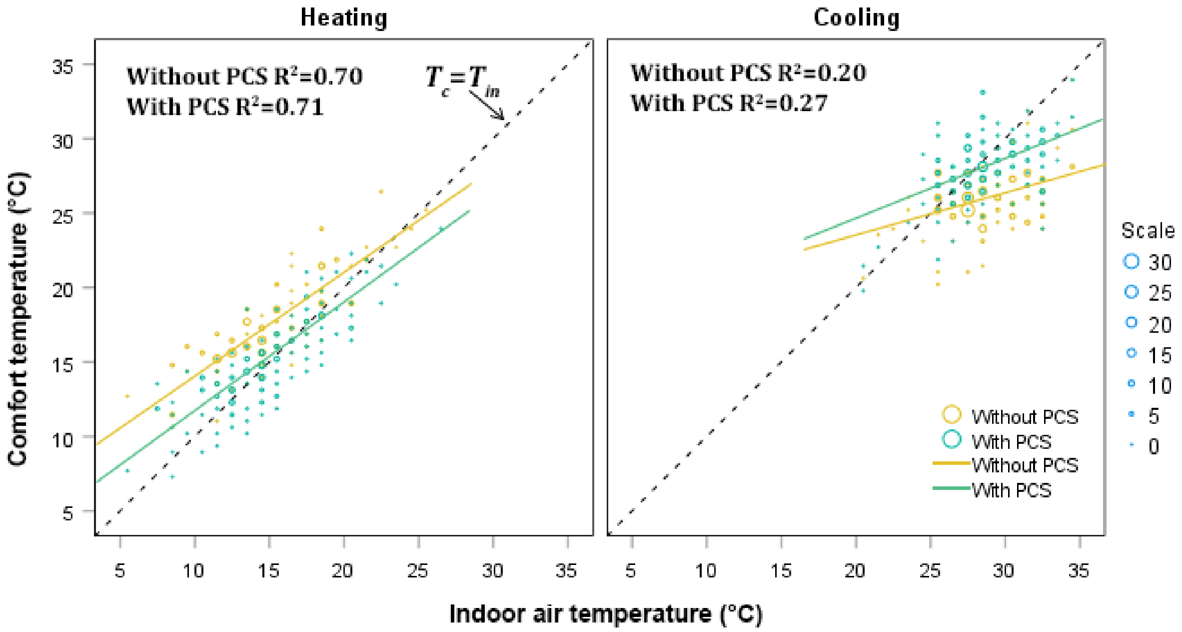

Figure 9. Relationship between the comfort temperature and indoor air temperature

comfort temperature and indoor air temperature compared to the heating mode. The slopes of both with and without PCS regression lines are higher in heating mode than those in cooling mode. The slopes with PCS conditions are consistently higher than those without PCS in both heating and cooling modes. This further confirms the improvement of comfort temperature done by PCS in heating and cooling modes toward lower and higher temperatures.

A shift in T_c of 1.9~2.5°C toward lower values was observed when PCS were used in heating mode, within an indoor air temperature range of 5 to 23 °C. In cooling mode, T_c shifted higher by 2.3~3.1 °C between 25 and 38 °C, further confirming the significant improvement made by PCS in both modes. This shift in comfort temperature facilitated by PCS can be applied in real-world settings to promote energy savings by lowering HVAC setpoints by 2–3 °C in cold environments and raising them by 2–3 °C in hot environments, as indicated by our findings. Even in a minimally conditioned space such as 17°C, PCS created a neutral environment by efficiently heating the hands through conduction and the ankles and face through radiation [95,96]. Participants sometimes experienced a warm sensation exceeding their needs in low indoor air temperatures [96]. Additionally, PCS have been found to reduce hot sensations and enhance comfort in hot environments. Notably, the combination of a radiant cooling desk and a desk fan has significantly extended the comfort temperature range up to 32°C [95]. Previous studies suggest that PCS effectively improve comfort by lowering comfort temperature in heating mode and raising it in cooling mode across a wide range of indoor air temperatures.

The findings of this section offer practical implications for designing buildings that maintain occupant comfort, while consuming low energy. PCS were found to significantly enhance thermal comfort by enabling individuals to regulate their immediate thermal environment. This capability is particularly valuable in spaces, where achieving uniform thermal conditions is challenging, due to diverse personal preferences or activity levels. PCS demonstrated effectiveness across a wide range of indoor temperatures (5-38°C), making them suitable for both heating and cooling applications. By integrating PCS, HVAC setpoints can be adjusted to 2 to 3 °C higher in warm environments and lower in cool environments, without compromising occupant comfort. These HVAC adjustments can lead to substantial energy savings, estimated at 20-30% of total building energy consumption, while also reducing the need for reliance on centralized HVAC systems [11].

3.4. Power and energy performance

CP analysis is essential for evaluating PCS performance, as it quantifies the extent to which individual thermal comfort can be enhanced through localized control of personal microenvironments. *CP* reflects the ability of a PCS to shift an occupant's thermal sensation toward a neutral thermal state within a given hot or cold environment [41]. Figure 10 shows a scatter plot of absolute *CP* across a range of indoor temperatures. In this study, absolute *CP* values of up to 6.5 °C were observed, when the indoor temperatures ranging from 5 °C to 38 °C, for both heating and cooling PCS devices. Even though the data points are scattered, the quadratic regression line reveals a clear trend: as indoor air temperatures deviate further from the neutral range, either decreasing or increasing, *CP* values rise smoothly. This pattern indicates that PCS are highly effective in maintaining thermal comfort under both warm and cold conditions, reinforcing their potential to enhance occupant satisfaction across diverse thermal environments.

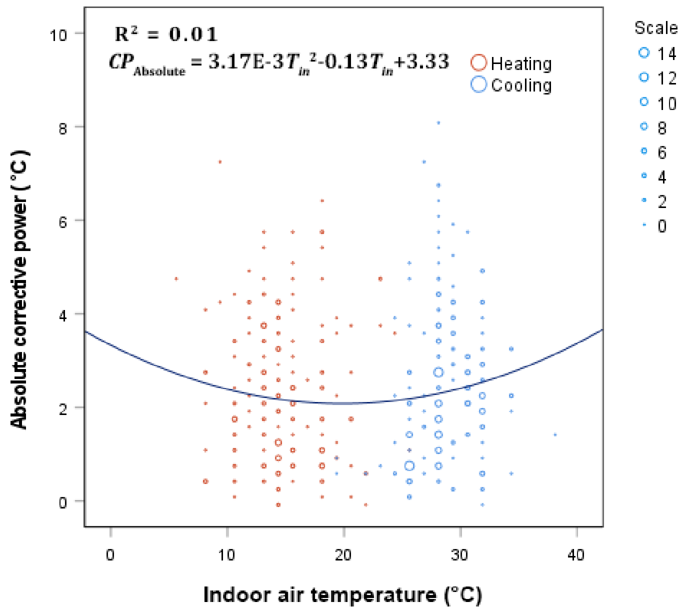

Figure 10. Relation between absolute corrective power and indoor air temperature

CEP is a widely used metric that links *CP* to the energy consumption of PCS devices [81,82]. Lower *CEP* values indicate systems capable of delivering effective thermal comfort with low energy use, making *CEP* a valuable metric for assessing energy efficiency across different PCS technologies. Among the analyzed studies, absolute *CEP* values of up to 500 W/°C were observed across indoor air temperatures ranging from 8 to 32°C for both heating and cooling devices.

Figure 11 shows a scatter plot of absolute *CEP* values against indoor air temperature for different PCS types, categorized by PCS type according to heat transfer mechanism. In heating mode, *CEP* values exhibited greater variability, reflecting the diverse range of device types and power ratings used. In contrast, CEP values in cooling mode were generally lower and more consistent, typically below 100 W/°C, due to the frequent use of low-power devices such as fans and cooling chairs. These findings suggest that heating PCS devices tend to consume more energy than cooling devices to achieve comparable improvements in thermal perception. Across all indoor air temperatures studied (8–

32 °C), the average absolute *CEP* was found to be 42.6 W/°C, reinforcing the potential of PCS to deliver energy-efficient thermal comfort.

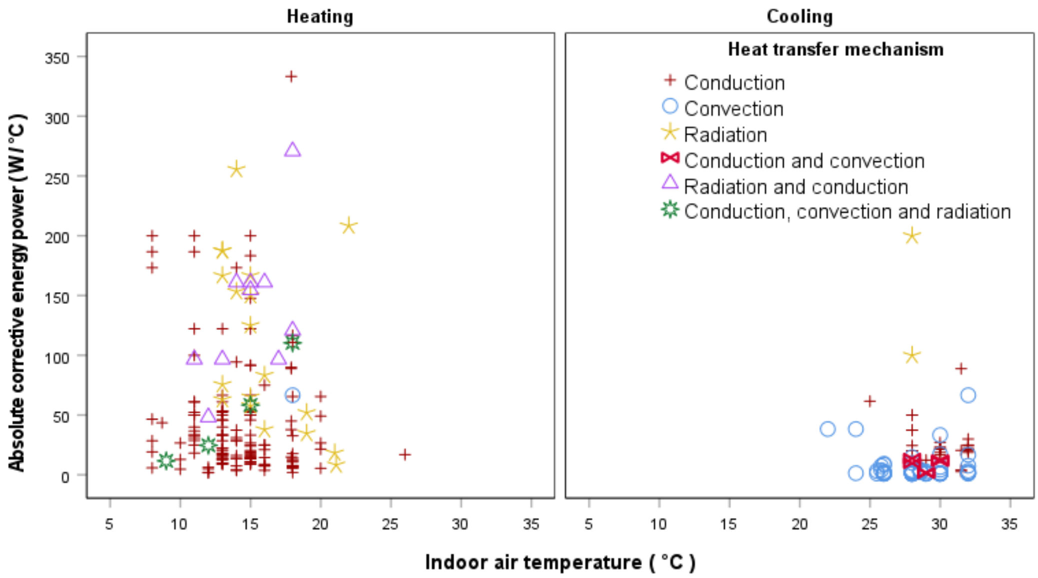

Figure 11. Absolute corrective energy power values for each indoor air temperature

A comparative analysis of heat transfer mechanisms of PCS reveals that radiation-based devices in PCS appear to require substantial energy expenditure to achieve a 1°C improvement in occupant thermal perception during both heating and cooling modes. In contrast, conduction-based PCS and combined heat transfer mechanisms such as conduction with convection, radiation with conduction, conduction with convection and radiation used in PCS demonstrate lower energy consumption for both heating and cooling modes. Convention-based PCS exhibit particularly efficient energy performance in cooling mode. This suggests that thermal comfort can be achieved at higher indoor air temperatures using low power-consuming cooling devices. However, heating devices consume slightly high power at lower indoor air temperatures. Also, these insights indicate that using conduction and combined heat transfer mechanisms in PCS is effective in both heating and cooling modes while the convection mechanism is well suited for the cooling mode. Overall results indicate that PCS can provide comfort in a wide range of uncomfortable indoor temperatures, consuming low power, almost less than 200 W/°C in both heating and cooling modes.

Absolute values of CP and CEP were employed in the figures to eliminate negative entries for cooling mode. However, cooling-mode data interpretation requires methodological caution, as decreasing ambient temperature values represent thermal improvements in cooling scenarios. While absolute value representation facilitates comprehension and enables cross-modal comparison of PCS performance between heating and cooling operations, this approach may inadvertently mask the directional nature of thermal enhancement trajectories illustrated in the graphical outputs.

The findings confirm that PCS consume less energy than traditional HVAC system, while effectively providing thermal comfort in both heating and cooling modes [97,98]. PCS were particularly beneficial in office, academic, residential, and commercial settings, where occupants engage in low-intensity activities and exhibit diverse thermal comfort preferences. Buildings with outdated HVAC systems can especially benefit from PCS integration, as these systems offer a practical solution for maintaining thermal comfort without requiring major infrastructure upgrades. Likewise, homeowners can adopt PCS to enhance personal comfort without requiring extensive HVAC modifications, leading to energy savings, improved overall comfort and potential health benefits [99].

4. Overall discussion and future work

4.1. PCS impact

The results of this review demonstrate that PCS significantly enhance thermal comfort, as evidenced by improvements in *TSV* and *OC* across a wide range of indoor air temperatures, consistent with previous research [10,36]. Regression analyses further confirm that PCS contribute to meaningful shifts in thermal perception. Even in extreme conditions, such as below 10 °C and above 35 °C, PCS achieved improvements of approximately 1~2 scale units in *TSV* and *OC* [55,60,71,73,81,100,101]. PCS also influenced T_c, lowering it under heating conditions and raising it under cooling conditions, with an average shift of approximately 2 °C. Veselý and Zeiler [9] reported that PCS can support indoor temperatures 4–5 °C above or below standard comfort thresholds, enabling HVAC setpoints to be raised by 2–3 °C in hot environments and lowered in cold environments without compromising comfort. This effect has been validated in previous studies examining PCS integration with HVAC systems [38,39].

In this study, the maximum *CP* was 8 °C with an average of approximately 2 °C aligning with findings from Zhang et al. [41]. Li et al. [102] found *CP* values ranging from 3. 1 to 6.8 °C at indoor temperatures between 16-20°C, while Wang et al. [103] found that PCS could deliver *CP* values up to 38.3 °C under extreme cold conditions, such as -20 °C. Most *CEP* values in this study were below 350 W/°C, although Song et al. [36] reported *CEP* values under 60 W/°C, and Li et al. [102] found all *CEP* values below 100 W/°C across four types of heating devices. Both *CP* and *CEP* tended to increase at temperature extremes, indicating that PCS are effective in enhancing comfort and energy efficiency in both hot and cold environments, a trend also observed in prior studies [36,43]. PCS were found to consumes less energy in cooling mode compared to heating mode, consistent with earlier findings [36].

The results also suggest that conduction and combined heat transfer mechanisms are energy efficient in both heating and cooling modes, while convection is particularly energy efficient in cooling applications. For the heating mode, Tang et al. [43] and Zhu et al. [57] identified conduction as the most effective heat transfer mechanism for improving *OC,* and Li et al. [102] reported that conduction yielded the lowest *CEP* values. For cooling, Enescu [104] found convection devices as highly effective, which was confirmed by Song et al. [36] that convective cooling devices have lower *CEP* values. These findings support the conclusion that PCS improve thermal comfort globally, while consuming less energy than traditional HVAC systems, making them a viable solution for a wide range of indoor thermal environments.

Most of the referenced studies were conducted in climate chamber settings; however, Sun et al. [105] found no significant difference in the performance of PCS between climate chambers and field experiments. In fact, greater comfort improvements may be achieved in real-world settings, due to adaptive occupant behaviors [83]. While the use of a constant sensitivity value in Griffiths' method may influence real-world interpretations of the results, Rijal et al. [106] demonstrated that when TSV is near neutral, the choice of sensitivity value has minimal impact on the overall estimation of T_c. This was consistent with Griffiths' constant values of 0.25, 0.33, and 0.50. Given that the mean and median TSV in this study are approximately zero, these findings are considered applicable to real-world conditions.

Most of the studies included in this meta-analysis originate from Asia, particularly China and Japan. Havenith et al. [33] observed that Asian users tend to prefer higher temperatures when using cooling PCS compared to European users. Similarly, Draganova et al. [107] reported differences in thermal sensitivity between Japanese students and those from other nationalities. Such individual differences may influence the interpretation and generalizability of the findings. However, Wang et al. [89] argued that comfort temperature preferences are primarily influenced by local climate, while thermal sensitivity is affected mainly by both building type and climatic conditions. Notably, this study includes data from various climate zones even within China. Further research is required to better understand the nuanced effects of climate and geographical region on PCS performance.

PCS are also well applicable in outdoor contexts and various activity-level scenarios. Gu et al. [108] found that wearable heating PCS significantly improve comfort in outdoor settings. Hossain et al. [109] reported that wearable cooling PCS enhanced comfort for construction workers, while Yi et al. [110] demonstrated that such systems provided higher comfort levels in warm environments, even during high physical activities.

Despite their benefits, PCS face several usability and scalability challenges. Usability issues include confusing or complex controls, uncomfortable or restrictive physical designs, limited personalization options, inconsistent performance related to providing comfort, and difficulty of use for less tech-savvy individuals [10,111]. Scalability challenges involve high costs, integration difficulties with existing HVAC systems, limited adaptability in shared spaces, increased maintenance demands, lack of industry standards and interoperability, and complex data modeling requirements for personalized comfort on large scales [21,23,112]. Even though these factors hinder both user satisfaction and broader adoption of PCS, the overall evidence supports the significant impact of PCS across various contexts.

There is also a lack of detailed guidelines and standards for PCS implementation. Existing thermal comfort standards offer conceptual frameworks and basic performance criteria for PCS, particularly emphasizing occupant control and comfort metrics. However, they do not yet provide comprehensive usage protocols for all types of PCS.

Ownership and long-term use of PCS may influence user perceptions over time. As users gain experience, their preferences and expectations evolve [113]. Previous studies have shown that individuals tend to habituate to thermal environments [114,115], which may reduce the perceived comfort benefits of PCS over time. Therefore, understanding the long-term effects of PCS on thermal perception remains an important area of future research.

4.2. New comfort performance metric

To evaluate the impact of PCS on thermal comfort, *CP* is commonly used as a thermal metric in studies. CP effectively captures the perceptual temperature difference induced by PCS, offering a valuable indicator of comfort enhancement. However, *CP* does not account for climatic or contextual factors that may influence PCS performance in specific environments. Since comfort temperature varies across different contexts, such as climate zones and countries [30], relying solely on *CP* to adjust HVAC setpoints may limit its applicability. Furthermore, the *CP* value of a given device can vary under different ambient conditions, limiting its generalizability. This variability can make it challenging for users to determine optimal HVAC setpoints during PCS operation, potentially undermining the energy-saving capability of PCS. This might affect the HVAC energy savings influenced by PCS negatively. If users can adjust the temperature setpoint to an optimal level during PCS operation, significant energy savings may be achieved in buildings.

To address these limitations, this study proposes a new metric: the Coefficient for Comfort Temperature Shift (*CCTS*). It quantifies the impact of PCS from the perspective of comfort temperature, incorporating factors such as climate-specific conditions and ethnicity-related occupant characteristics. This metric can support the design of context-specific PCS and help estimate optimal HVAC temperature setpoints across diverse environments. For ideal performance:

- *CCTS* should be less than 1 in cooling mode, indicating a constructive shift toward higher comfort temperatures.

- *CCTS* should be greater than 1 in heating mode, reflecting a beneficial shift toward lower comfort temperatures.

Figure 12 illustrates the relationship between *CCTS* and indoor air temperature using both original and binned data. The slopes for heating and cooling modes follow similar trends, with CCTS values increasing at higher indoor temperatures and decreasing at lower ones. This pattern suggests that PCS performance, as measured by *CCTS*, is enhanced at temperature extremes, reinforcing its value as a performance indicator. These findings align with the ideal performance of PCS, emphasizing the effectiveness of PCS. Therefore, the *CCTS*-based equations may have global applicability for evaluating PCS performance. This parameter serves as an indicator of the thermal comfort performance of PCS. It can be utilized by designers and engineers to estimate energy use and thermal comfort improvements across different indoor temperatures. Manufacturers could experimentally determine and define *CCTS* values, enabling standardized performance assessments, particularly for climate-specific applications. Ultimately, *CCTS* will be valuable for PCS manufacturers and designers in optimizing system performance and efficiency.

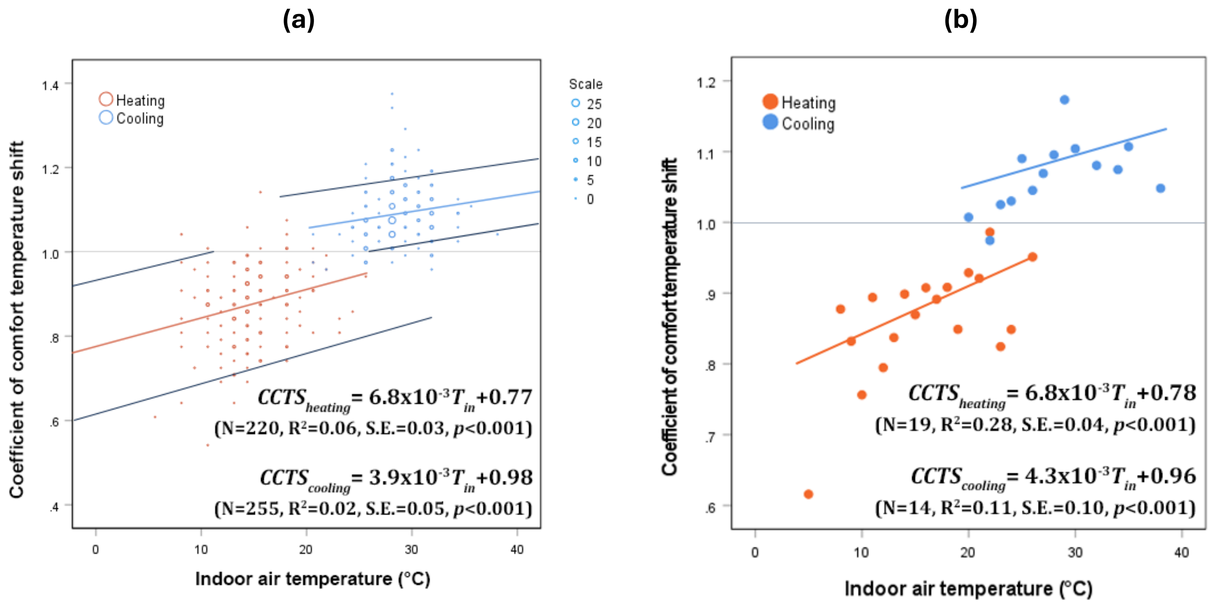

Figure 12. Relationship between the coefficient of comfort temperature shift (*CCTS*) and indoor air temperature of PCS: (a) Original data and (b) Binned data

As an implication, the *CCTS* metric provides a standardized measure applicable to any PCS used for both heating and cooling purposes. It offers valuable insights into optimal indoor temperature setpoints for HVAC systems, enabling more precise and energy-efficient thermal management. The practical implementation of *CCTS* requires adaptation across both manufacturing and end-user contexts. Manufacturers should provide standardized *CCTS* values for their PCS products, derived through systematic human subject trials conducted under controlled experimental conditions or field studies. For each distinct PCS configuration, *CCTS* values can be empirically determined through rigorous human thermal comfort assessments, ensuring validity and applicability across diverse operational environments. Once the *CCTS* value is known, users or designers can determine the optimal indoor temperature setpoint using the following equation:

$$T_{in\ setpoint\ with\ PCS} = CCTS \times T_c \tag{13}$$

If this T_c value can be substituted with comfort temperature in a particular context, then the obtained new HVAC set points would be the optimal comfort temperature with PCS. This formulation enables more efficient temperature management, contributing to enhanced thermal comfort and energy savings in building environments.

Table 2 presents a comparative framework of PCS performance metrics, highlighting the unique advantages of the newly introduced *CCTS*. Unlike traditional metrics, the *CCTS* metric uniquely enables direct thermostat setpoint determination, distinguishing it from existing performance metrics. For instance, if a cooling PCS has a CCTS value of 1.1 and the occupant's comfort temperature is 25 °C, Equation (13) yields a setpoint of 27.5 °C. Conversely, for a heating PCS with a CCTS value of 0.9 and a comfort temperature of 22 °C, the calculated setpoint is 19.8 °C. Occupants can directly apply these calculated values to HVAC thermostat settings when operating PCS, thereby optimizing energy savings while maintaining thermal comfort. This approach mitigates the risk of HVAC misoperation in PCS-integrated environments. However, further empirical validation of the CCTS metric is necessary. Future research should aim to establish comprehensive guidelines for its practical application across diverse building types, climatic conditions and user populations.

Table 2. Comparison of current performance evaluation metrics for PCS and newly introduced CCTS

Performance metric	Thermal sensation	Comfort temperature	Energy efficiency of PCS	HVAC integration	Setpoint determination	Primary objective
Corrective Power (CP)	✓	✗	✗	✗	✗	Quantifies the magnitude of ambient temperature shift toward thermal neutrality induced by PCS operation
Corrective Energy Power (CEP)	✓	✗	✓	✗	✗	Quantifies the per person power consumption required to achieve a 1°C shift toward thermal neutrality.
Coefficient of Comfort Temperature Shift (CCTS)	✓	✓	✗	✓	✓	Establishes the direct relationship between HVAC setpoint temperature and occupants' comfort temperature

4.3. Limitations and future directions

While this meta-analysis provides valuable insights into PCS performance, several limitations should be acknowledged. Most of the included studies were conducted in climate chambers or semi-controlled settings, which may limit generalizability of findings to real-world building contexts [116]. Additionally, over 50% of studies originated from China and the U.S., with limited representation from extreme climates or diverse cultural comfort preferences [33]. Due to the limited availability of thermal parameters, such as air quality, thermal acceptability, thermal preference and other physiological parameters, this study relies on *TSV* and *OC,* potentially overlooking other subjective and contextual factors [26]. The use of absolute *CP* and *CEP* values may also obscure the directionality of thermal improvements, complicating interpretation. Furthermore, the Griffiths constant (a = 0.33) was uniformly applied, , without accounting for individual and contextual variations in thermal sensitivity [78]. Most studies were short-term experiments, which do not capture the long-term effects of PCS usage, such as habituation, adaptation, behavioral changes, or device degradation over time [117,118].

Future research should prioritize conducting more field studies in real-world environments, such as offices, homes, and schools, to validate findings from climate chamber experiments and assess the adaptability of PCS across diverse populations. Longitudinal studies are needed to explore how users engage with PCS over time, including adjustment behaviors and their impact on energy consumption. Research should also focus on identifying optimal PCS integration strategies within HVAC systems, considering various PCS types and operational contexts. Incorporating physiological measurements, such as skin temperature and heart rate variability, alongside subjective comfort assessments will enable a more comprehensive evaluation of thermal comfort. Further investigation into AI-driven PCS control strategies could enhance the interaction between HVAC systems and PCS, maximizing both energy efficiency and occupant comfort. Evaluating hybrid PCS solutions, such as systems combining several heat transferring mechanisms targeting multiple body parts, may enhance efficiency and user satisfaction. Establishing industry standards for PCS performance metrics, such as *CPE* and *CCTS,* will support manufacturers and policymakers in evaluating and promoting PCS technologies. *CCTS* and *CPE* parameters could also be integrated into future simulation tools to support design and operational decisions. Finally, future research should explore PCS' energy performance across different occupancy levels and building types, helping to identify optimal deployment strategies for maximizing energy savings and comfort.

5. Conclusions

This meta-analysis systematically evaluated the effectiveness of Personal Comfort Systems (PCS) in enhancing thermal comfort and energy performance across a range of environmental and behavioral conditions. The findings are as follows:

1. PCS significantly enhance thermal comfort by improving approximately 1 scale unit in the 7-point scale of thermal sensation vote (TSV) and overall comfort (OC) across a wide range of indoor temperatures. PCS also shift comfort temperatures by 2.2 °C in heating mode and 2.1 °C in cooling mode, enabling broader thermal adaptability.
2. The shift in comfort temperature facilitated by PCS can be applied in real-world settings to enhance energy savings by adjusting HVAC setpoints—lowering them in cold environments and raising them in hot environments by 2–3 °C, without compromising occupant comfort.
3. Corrective powers (CP) were found up to 8 °C, and almost all corrective energy power (CEP) values were found below 350W. Both metrics demonstrated high effectiveness under extreme thermal conditions, confirming PCS capability to maintain comfort in non-neutral thermal environments, while consuming significantly less energy than traditional HVAC systems.
4. Conduction-based and hybrid PCS were found to be highly energy efficient in both heating and cooling modes, while convention-based PCS were particularly efficient in cooling mode.

5. The introduction of the Coefficient of Comfort Temperature Shift ($CCTS$) provides a standardized metric for evaluating PCS performance. $CCTS$ offers practical guidance for optimizing HVAC setpoints and achieving energy savings. It can assist designers, engineers, and manufacturers in developing more energy-efficient and adaptive PCS tailored to specific applications.

In summary, PCS represent a promising solution for enhancing thermal comfort and energy efficiency in buildings. By enabling individualized thermal control and reducing reliance on centralized HVAC systems, PCS contribute to sustainable building practices and enhanced occupant well-being. Future research should focus on further optimizing PCS design, exploring adaptive systems, and expanding their application to diverse populations, climates and environments. The findings of this study underscore the importance of integrating PCS into building design and operation to achieve both comfort and energy savings across various countries, climates and contexts. The widespread adoption potential of PCS is likely to make a significant contribution to global energy reduction efforts. Designers and policymakers can leverage efficient PCS to raise central HVAC setpoints by 2–3 °C in warm environments and lower them in cold environments, thereby achieving substantial reductions in HVAC energy consumption in buildings.

Acknowledgements

The authors extend their sincere appreciation to the researchers whose exceptional work on Personal Comfort Systems (PCS) has significantly advanced this field. Their rigorous methodologies, insightful analyses, and openly shared data provided a critical foundation for this meta-analysis and greatly enriched the outcomes presented.

Appendix

Table A1. Basic information on previous PCS studies

Reference	Type	Mode	Experiment type	Heat transfer method	Climate Type	Country	Indoor air temperature (°C)	Number of subjects	Number of male/ females	Relative humidity	Air velocity (m/s)	Activity (Met)	Clothing insulation (Clo)	Power values (W)
Zhai et al. [56]	Floor fan	CL	CC	CV	Csb	USA	26,28,30	16	M-8, F-8	60,80	0.4,0.5,0.7,0.8,1.1,1.3	***1***	0.5	2.8,3.3,4.8,5.7,7.9,10.3
Huang et al. [67]	Frontal desk fan	CL	CC	CV	Dwa	China	28,30,32,34	30	M-15, F-15	45	0.6, 1, 1.5, 0.5, 2, 1.6, 1.9	1.1	0.57	NA
Cui et al. [119]	Fan Simulated natural wind, Constant mechanical wind	CL	CC	CV	Dwa	China	28	18	M-12, F-6	40	***1.1***	***1, 1.1***	0.7	NA
Arens et al. [38]	Opposing air jets	CL	CC	CV	Csb	USA	28	18	M-9, F-9	50	0.6, 1, UC	***1.1***	0.5	NA
Atthajariyakul et al. [53]	Desk fan	VT	FE	CV	Aw	Thailand	25,26,27,28	15	M-10, F-5	60,70,72.5, 75	0.5, 1, 1.5, 2	1	0.6	NA
Zhang et al. [60]	Local airflow	CL	CC	CV	Dwa	China	35	30	M-30	40	0.1<	***1***	***0.3***	NA
Amai et al. [120]	Task conditioning system/Personal environmental module/Under-desk task unit/Remote control unit/ +Mesh four terminal Devices	CL	CC	CV	Cfa	Japan	28	24	M-12, F-12	50	Calm flow	1.2	0.7,0.4	NA
Zhai et al. [121]	Ceiling fan	CL	CC	CV	Csb	USA	26, 28, 30	16	M-8, F-8	60,80	0.3, 0.7,0.9,1.2,1.6,1.8	***1.1***	0.5	NA
Kubo et al. [122]	Uniform airflow on whole body	CL	CC	CV	Cfa	Japan	26, 28, 30	4,9,8,6	F	50, 80, 30	0.6, 0.7, 0.9, 1, 1.1, 1.3	***1***	0.3	NA
Zhang et al. [20]	Foot warmer	HT	FE	RD	Csb	USA	30	12	M-6, F-6	NA	NA	***1.1***	***0.6***	11, 5

Watanabe et al [123]	Cooling chair	CL	CC	CV	Cfa	Japan	28, 30, 32	7	M-7	50	NA	***1***	0.63	NA
Brooks et al. [100]	Heated seat	HT	CC	CD	Dfb	Canada	5, 10, 15, 20	8	M-8	40	<0.2	***1***	0.93	NA
Su et al. [124]	Convection and radiation combined terminal device - Fixed/User control	HT	CC	CV and RD	Cwa	China	14, 16, 18, 20	16	M-8, F-8	45	<0.1	***1.1***	1.22	NA
Shahzad et al. [125]	Thermal chair	HT	FE	CD	Cfb	UK	24.1	44	M-29, F-15	30	0.1	***1***	0.7	NA
Du et al. [72]	Local warm air supplier. Supply air temperature 32,42,52,28,34,40,26,30,34, 22 °C	HT	CC	CV	Cfa	China	12, 14, 16, 18	20	M-10, F-10	60	<0.1	***1***	1.3	NA
Zhu et al. [57]	Radiant panel low/high/ heating plate/ fan heater	HT	CC	RD/CD/ CV	Cfa	China	14	20	M-10, F-11	60	<0.1	1.1	1.3	230, 170, 450, 230
Song et al. [59]	Hybrid personal cooling garment	CL	CC	CD and CV	Cfa	China	34	11	M-11	65	0.2	***1.1***	0.7	NA
Verhaart et al. [126]	Personalized air movement. 23/26 °C supply temperature	CL	CC	CV	Cfb	Netherlands	27	12	M-5, F-7	NA	1, 1.1	***1.1***	0.6	NA
Kaczmarczyk et al. [127]	Personal ventilation supply temperature 21,26 °C	VT	CC	CV	Cfb	Denmark	27	32	M-16, F-16	30	0.4	***1.1***	0.8	NA
Li et al. [73]	Foot heating pad - constant heating 30 W,90 W, high/low and fluctuating frequency heating	HT	CC	CD	Cfa	China	8, 11, 14	16	M-8, F-8	60	NA	***1.1***	1.35	52, 56, 60
Pasut et al. [128]	Ceiling fan 2/3 Oscillating/Fixed front/side/below	CL	CC	CV	Csb	USA	28	16	M-8, F-8	50	OSC/0.7, 0.9,0.8,	***1.1***	0.5	2, 3
Luo et al [54]	Heating desk, heating mat and ventilation fans	HT	CC	CD and CV	Cfb	Netherlands	17, 19, 21, 23, 25	18	M-9, F-9	48	0.2	1.2	0.8	NA
Tang et al. [43]	Warm air blower/radiant heater/heated cushion/desk/floor fan, ventilated cushion	HT/CL	CC	CV/ CD/RD	Cfa	China	18, 22	28	M-14, F-14	50	<0.1	***1***	0.6	3.3, 10.1, 29.9, 43, 420, 630

Lee et al. [129]	Ventilation seat/ cold water seat/ electric heating/ hot water	CL/HT	CC	CV	Cfa	Korea	22.5, 27.5	20	M-11, F-9	50	0.1	1.8	0.44,0.68	NA
Pallubinsky et al. [130]	Face cooling/back cooling/ foot sole cooling/ face underarm cooling	CL	CC	CV	Cfb	Netherlands	32.3	16	M-8, F-8	29.3	NA	1.2	0.64	NA
Veselý et al. [40]	Heated chair/desk mat/floor mat/ combination user controlled/fixed/automated	HT	CC	CD	Cfb	Netherlands	17.9	13	M-7, F-6	48	<0.2	1.2	0.7	36, 80, 100, 216
Udayraj et al. [58]	Radiant heating panel with table pad/ heated chair with heated floor mattress/Heated jacket and heated trousers/radiant heating panel with table pad	HT	CC	RD and CD/CD	Cfa	China	15, 18	14	F-14	50	<0.1	***1***	0.99	16, 133, 325
Yang et al. [131]	Footwarmer normal shoes/sandals	HT	CC	RD	Dfc	Sweden	16, 19, 22	32	M-16, F-16	45.5, 41.2, 39.6	NA	***1.1***	1	125
Wang et al. [132]	Radiant/ wrist/ ankle/ torso/ combined heating	HT	CC	RD/CD	Cwa/ Dwa	China	13, 15	20	M-10, F-10	43.7, 37.8	<0.1	1.2, 1.45, 1.69	1.25, 1.27, 1.42, 1.29, 1.44	450, 16, 20, 60, 36, 80, 76
Song et al. [55]	Electrically heated/ chemically ensemble	HT	CC	CD	Cfa	China	8	8	M-8	80	0.17	1.3, 1.2	1.72, 1.76	15.9
Tang et al. [133]	Cooling air towards the breathing zone/ chest and back/ combined	CL	FE	CV	NA	China	32	28	M-14, F-14	50	<0.1	1.1	0.5	NA
Zhao et al. [71]	Ventilation cooling shirt	VT	CC	CV	NA	NA	38	8	F-8	45	0.4	***1.1***	0.8	NA
He et al. [95]	Radiant cooling desk, local airflow 1.6,2.2 m/s, combined	CL	FE	RD/CV/ RD and CV	Cfa	China	28, 30, 32	20	M-10, F-10	60	<0.1	1	0.5	2, 3
Verhaart et al. [134]	Personalized air movement 23/25/26 °C, Supply temperature 30/90min	CL	CC	CV	Cfb	Netherlands	27.6	11	M-5, F-6	23	0.9,1.3	***1.1***	0.6	NA
Yu et al. [135]	Heated floor panel and insulated chair	HT	FE	CD	Cfa	China	16	10	NA	NA	0	***1.1***	1.35	30

Yang al. [37]	Table pad, backrest, cushion heaters, and leg warmer	HT	FE	CD and RD	Cwa	China	11-18	8	M-4, F-4	27.2	NA	1.2	1.42,1.39,1.37,1.41,1.42,1.32	145
Kimmling et al. [61]	Thermoelectric cooling partition 50, 100 % cooling power	CL	FE	RD	Cfb	Germany	28	7	NA	41	NA	***1.1***	NA	60
Sun et al. [136]	Displacement Ventilation System	VT	CC	CV	NA	NA	22, 24, 26	32	M-16, F-16	NA	NA	***1.1***	0.5	23
He et al. [137]	Desk fan 1.5, 2.3 m/s, User controlled	CL	CC	CV	Cfa	China	26, 28, 30	24	NA	80	1.5,2.3,0.63,1.13,1.42	1	0.5	0.8, 1.5, 1.8, 2, 3
Ren et al. [62]	Heating plates 1-4/2-4	HT	FE	RD	Cwa/ Cfa	China	13, 15	20	M-10, F-10	68,67,73,72	0.02, 0.03	***1.1***	1.23	156.5, 170.1, 208.4, 226.8
Li et al. [138]	Under-floor air distribution 22/18 °C +Personalized ventilation 26/22 °C -5/10 L/s	VT	CC	CV	NA	NA	26	30	M-15, F-15	NA	NA	***1***	0.59	NA
Akimoto et al. [139]	Task ambient system	CL	FE	CV	Cfa	Japan	28	20	M-12, F-8	50	Very low	1.4	0.56	NA
Schiavon et al. [74]	Stand fan	CL	CC	CV	Af	Singapore	26, 29	56	M-28, F-28	60	0.6, 1	1.1	0.7	4, 7.6
He et al. [140]	Radiant cooling desk	CL	CC	RD	Cfa	China	28, 30, 32	20	M-10, F-10	60	<0.15	1	0.5	NA
Wang et al. [132]	Local heating floor mat small/ large - low/high power	HT	SFE	CD	Cwa/ Dwa	China	11, 13, 15	16	M-8, F-8	40	0.1	1, 1.4, 2	1.26	60, 110
Oi et al. [141]	Seat/ foot warmer / combined	HT	CC	CD	Cfa	Japan	10, 20	8	M-8	50	0.1	***1***	1	10, 48, 58
He et al. [81]	Retrofitted Huotong	HT	CC	CD, CV, and RD	Cfa	China	9, 12, 15, 18	16	M-16	50	0.05	1	1	49.4, 104.1, 140.3, 165.7
Yang et al. [142]	Heated chair equipped with backrest and seat heating cushions	HT	CC	CD	Dwa	China	14, 16, 18	13	M-7, F-6	50	0.1	***1***	0.95	90
He et al. [143]	Heating chair /heating chair +leg-warmer	HT	SFE	CD	Cfa	China	14, 16, 18	12	M-6, F-6	60	<0.1	1	1.1	19.4, 25.3,

														25.4, 34.1, 34.9, 41.1
Pasut et al. [144]	Heated/cooled chair + cover/clothing/fan	HT/CL	CC	CD	Csb	USA	16, 18, 29	23	M-11, F-12	50	<0.1	***1.1***	0.8,1, 0.5	3.6, 16
Zhang et al. [145]	Task–ambient conditioning (TAC) system	HT/CL	CC	CD/ CD and CV	Csb	USA	18, 20, 24.5, 28, 30	18	M-9, F-9	NA	NA,1	***1.1***	0.6,0.5	59,41,
Luo et al. [42]	Heating Insoles/ wrist pad/ chair heating/ combined/ fan/ chair cooling/ combined	HT/CL	CC	CD/CV/ CV & CD	Csb	USA	18, 29	20	M-10, F-10	40	NA	***1***	0.65,0.5	2.4, 7, 9.4, 16.4, 21, 23.4, 4.4, 5.6, 8
Pasut et al. [146]	Thermoelectric chair	HT/CL	CC	CD	Csb	USA	16, 18, 25, 29	30	M-14, F-16	50	<0.1	***1.1***	0.65,0.5	42, 74
Yang et al. [147]	Back, Buttock, Combined cooling	CL	CC	CD	Dwa	China	28, 30, 32	16	M-16	NA	<0.1	1.1	0.4	54.5,54.8, 66.2, 61.9, 64.6, 83.2, 72.5, 73.3, 97.7
He et al. [148]	Desk fans/ desk fans+ AC	CL	SFE	CV	Cfa	China	26, 28, 30, 25.5, 25.8, 25.9	16	M-7, F-8	55	0.8, 1.75, 1.3, 1.8, 1.5, 2.1	1	0.5	0.7, 1.1, 1.2, 1.4, 1.9, 2.2, 2.4, 2.9
Ke et al. [149]	Nanoporous polyethylene clothing	CL	CC	CD	Cfa	China	23, 25, 27, 29	18	F-18	60	<0.1	1.1	0.5	NA
H Yang et al. [150]	Chest/ abdomen/ upper back/ lower back cooling	CL	CC	CD	Dwa	China	28, 30, 32	20	M-10, F-10	50	<0.1	1.1	0.5	45
Udayraj et al. [151]	Ventilation clothing/ desk fan	CL	CC	CV	Cfa/ Cwa	China	28, 30, 32	14	F-14	50	<0.1	1	0.66	5.17, 40
Liu et al. [82]	Neck cooler, fan	CL	FE	CD, CV	Cfa/ Cwa	China	32	14	M-7, F-7	69.3	<0.1	1.8	0.4	NA
Wu et al. [152]	Fan	CL	CC	CV	Dwa	China	24, 26, 28, 30, 32	12	M-12	50	1	1.1	0.57	3
Ilmiawan et al. [153]	Fan: Different directions	CL	SFE	CV	Af	Malaysia	28.6	20	M-10, F-10	61	1.52, 1.56, 1.52, 1.51, 1.77,	1.1	0.47	15

											1.78, 1.74, 1.51			
Wu et al. [101]	Heating pad with and without air condition	HT	CC	CD	Cfa	China	8.7,16	12	M-8, F-4	50	NA	1	1	20.9
Yang et al. [154]	Wristband, leg band, insole, warm air blower, radiant heater, combined heating	HT	CC	CD	Cfa	China	12, 14	26	M-13, F-13	54.9, 55.2	<0.1	1	1	4, 5, 10, 19
Belyamani et al. [155]	Thermoelectric heat pump module	CL	CC	CD	Dfb	USA	31.5	60	M-35, F-25	30	NA	1.1	0.36	8

NA: Not Available, M: Male, F: Female, UC: User controlled, Cl: Cooling, HT: Heating, VT: Ventilation, CD: Conduction, CV: Convection, RD: Radiation, CC: Climate chamber, FE: Field experiment, SFE: Semi field experiments (conducted in real world conditions but controlled environments), ***Bold Italic***: Values were not been provided in original article and estimated using mentioned methods.

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