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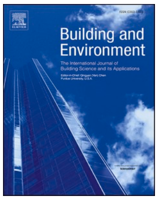

Personalized Environmental Control Systems (PECS): Systematic review of benefits for thermal comfort, air quality, health, and human performance

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ABSTRACT

Advances in environmental technologies have improved indoor environmental quality (IEQ) by creating steady, uniform conditions. However, these often fail to meet individual thermal comfort and air quality needs, prompting a shift toward adaptive, personalized solutions. Personalized Environmental Control Systems (PECS) aim to enhance comfort, air quality, health, and productivity through user-centered designs. This paper systematically reviews 324 journal articles on PECS from 1988-2023, focusing on thermal and indoor air quality (IAQ) domains. PECS are classified by mobility: building-attached, semi-attached, detached, and wearable. The review assesses their impact on thermal comfort, IAQ, health outcomes (e.g., Sick Building Syndrome, heat stress), and human performance (e.g., cognitive function, productivity). Results show that building-detached PECS often improve thermal sensation, comfort, and acceptability, with combined systems yielding better ratings. Personalized ventilation enhances IAQ by delivering clean air directly to the breathing zone, reducing contaminant exposure. Research on PECS effects on health is limited, mainly focusing on short-term, controlled studies. Evidence for benefits on human performance is sparse but promising. Key challenges include inconsistent performance metrics, limited real-world evaluations, and potential publication bias toward positive results. This review highlights the need for standardized evaluation methods, deeper understanding of combined PECS effects, real-world and long-term testing, and clearer quantification of human performance benefits to advance the field.

Nomenclature

ASHRAE	American Society for Heating, Refrigeration, and Air-Conditioning Engineers
AT	Air Treatment
ATD	Air Terminal Device
BZ	Breathing Zone
CFD	Computational Fluid Dynamics
CRE	Contaminant Removal Effectiveness
DV	Displacement Ventilation
EBC	Energy in Buildings and Communities
EEG	Electroencephalogram
ER	Exposure Reduction
HVAC	Heating, Refrigeration, and Air-Conditioning
IAQ	Indoor Air Quality
IEA	International Energy Agency
IF	Intake Fraction (-)
IoT	Internet of Things
KPI	Key Performance Indicator
MV	Mixing Ventilation
OAS	Outdoor Air Supply
PAQ	Perceived Air Quality
PCG	Personal Cooling Garment
PCM	Phase Change Material
PE	Personalized Exhaust
PECS	Personalized Environmental Control System
PEE	Personal Exposure Effectiveness
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
PV	Personalized Ventilation
RMP	Round Movable Panel
SBS	Sick Building Syndrome
TAV	Thermal Acceptability Vote
TCV	Thermal Comfort Vote
TSV	Thermal Sensation Vote
UFAD	Underfloor Air Distribution
VDG	Vertical Desk Grill
VEE	Ventilation Effectiveness
VOC	Volatile Organic Compounds

1. Introduction

1.1. Overview of reviews on personalized environmental comfort systems

Advances in building technologies, driven by industrialization throughout the 20th century, have significantly enhanced both living and working conditions by enabling improved control over indoor environmental quality [1]. Initially, indoor environments were designed based on assumptions of uniformity and steady-state conditions, as exemplified by the widely applied Predicted Mean Vote/Predicted Percentage of Dissatisfied (PMV/PPD) thermal comfort model [2] and conventional Heating, Ventilation, and Air-Conditioning (HVAC) methods designed to uniformly condition and ventilate entire spaces [3]. Later in the century, extensive standardization efforts by organizations such as ASHRAE and ISO further promoted uniform indoor conditions, resulting in the homogenization of building environments worldwide [4]. Early initiatives to standardize indoor environments introduced stricter conditions than before, substantially improving comfort and environmental quality. However, by the end of the 20th century, new challenges had emerged. As evidenced by multiple field studies [5,6], buildings that are supposedly designed according to standardized requirements do not necessarily provide a satisfactory experience to all their occupants, most often, because of individual differences in environmental perception and evaluation [7–9]. Furthermore, buildings with conventional mechanical ventilation methods have proven to be inefficient in providing pollutant-free air for healthy breathing. Clean, typically cool air is delivered from distant supplies such as ceiling, wall, or floor diffusers, and mixes with room air, becoming warmer and potentially contaminated (including with airborne pathogens exhaled, coughed, or sneezed by infected individuals) before reaching occupants [10]. These challenges highlighted the limitations inherent in uniform and steady-state approaches, prompting a shift toward more adaptive, personalized solutions. Dear et al. [11], in their overview of the developments in thermal comfort research between 1993 and 2013, emphasized not only the rise of the adaptive thermal comfort model but also the increased focus on non-uniform and non-steady-state thermal environments. Crucially, this shift included greater attention to human physiology and its influence on achieving effective comfort. Within the evolving context of research and development, characterized by diverse individual comfort needs, concepts such as personal comfort systems (PCS), personalized ventilation (PV) systems, personalized climatization systems, task/ambient air conditioning (TAC) systems, and localized conditioning systems emerged organically over the last few decades. The term "Personalized Environmental Control Systems" (PECS) was recently proposed within Annex 87 "*Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems (PECS)*" supported by the Energy in Buildings and Communities (EBC) Program of the International Energy Agency (IEA), and the term was accepted as a *unified framework* that broadly encompasses related concepts and terms found in previous literature.

The development of PECS can be traced back to the 1970s, with cooling garment systems being developed to mitigate workers' heat stress [12] and the first systems designed for office workstations [13], demonstrating their applicability in various contexts. Additionally, PECS studies were motivated by aspirations to operate buildings in mixed mode [14], thereby offering occupants healthier, individually controlled micro-environments that reduce exposure to air contaminants originating outdoors or indoors. Recent fundamental changes in building design and operation, accelerated by the pandemic [10,15,16], have further intensified interest in PECS, reinforcing the need for personalized environmental control solutions. The PECS concept pertains not only to thermal and air quality domains, but it can also be used in a holistic approach to improve the visual and acoustic conditions. An example is the successful integration of task lighting with ambient and accent lighting in buildings [17–19]. There have been many peer-reviewed papers on the PECS in the recent past, focusing primarily on PECS effectiveness and feasibility for improving comfort and achieving energy efficiency in buildings and vehicles, and comparing with conventional HVAC systems [20–24]. Predominantly, assessment of thermal comfort is a recurring theme across multiple review papers, with some addressing localized comfort and associated energy performance [8,13,25–28]. Several review studies, such as [29,30], delve into thermo-physiological parameters and experimental frameworks for personal comfort modules. Few review studies, such as [31–34], focused on personal cooling garments (PCGs), categorizing them by cooling materials and techniques, working principles in terms of heat transfer modes, and performance metrics such as energy efficiency, energy use, and feasibility to operate in real-world scenarios. Expanding the scope of PECS from just thermal performance to energy performance, several papers reviewed studies centered on indoor air quality (IAQ). A review of air distribution systems by Yang et al. [34] marginally touches on the IAQ domain. At the same time, other studies, such as [35–38], explored the integration of PECS with ventilation systems, highlighting localized air distribution strategies and their effects on IAQ, pollutant removal efficiency, and thermal stratification. However, discussions on pollutants or health impacts like Sick Building Syndrome (SBS) are rather sparse and could potentially be envisaged as a future research direction. A comprehensive analysis that integrates these dimensions to assess the cumulative impact of PECS on thermal comfort, IAQ, health, and work performance is lacking; hence, the systematic literature review and meta-analysis outlining the strategies, advancements, and performance evaluation of PECS regarding personalized IAQ is also challenging to find and not available. It is worth noting that most of the IAQ integration within the PECS has been envisaged as part of a very controlled indoor environment and management of indoor air pollution or contamination; however, health and well-being are suggested mainly as future research areas by most review papers. It is also worth noting that, apart from the thermodynamic aspect of the PECS, few researchers have focused on controlling the PECS using electronics and communication systems. André et al. [39] reviewed many studies on the use of personal comfort models associated with environmental control for system automation, as well as the development of new technologies that facilitate data acquisition and the proposition of new personal conditioning systems. Liu et al. [40] examined control strategies for PECS, including manual controls, sensor-based automation, and AI-driven adaptive systems. They emphasize that integrating IoT (Internet of Things) technologies and control systems has become essential to PECS implementation.

Despite the breadth of information covered in existing review papers, several gaps remain. First, the current body of literature on Personalized Environmental Comfort Systems (PECS) is highly fragmented, with studies often confined to isolated research aspects. This absence of an integrated, holistic perspective hinders a complete understanding of PECS and their broader impacts. Second, while comfort and energy efficiency have been widely addressed, the impact of PECS on other human-related effects such as cognitive performance and work productivity remains largely unexplored, despite their relevance to occupant well-being. Third, there is a notable absence of a comprehensive framework that connects PECS usage to measurable human outcomes, such as health, performance, and satisfaction. Such a framework is essential to assess the actual value of personalized environmental controls. Lastly, most existing reviews adopt a single-domain approach, focusing either on thermal comfort or indoor air quality (IAQ), even though these factors are often interrelated in real-world settings [41].

1.2. Objectives and research questions

As the primary aim of PECS is to provide better comfort and improved well-being to individuals, this review uniquely adopts a holistic approach by exploring how PECS affect human comfort, health, and performance. This particular work focuses on thermal and IAQ domains, often closely linked, and pursues the following main objectives:

1) Systematically identify original studies on PECS that examine their effects on humans
2) Assess the extent to which previous research has addressed human comfort, performance, and well-being in relation to PECS
3) Apply the new categorization of PECS per their mobility and identify the PECS types and operational conditions providing human-related benefits
4) Identify existing knowledge gaps and propose future research directions in the field of PECS.

By bridging the technical overview of PECS with human responses, this review aims to assess whether existing research provides enough insight to inform the design of more responsive and user-focused indoor environments.

This work is a result of a systematic literature review on PECS research over the past 2 decades, and it was conducted within Annex 87 "*Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems (PECS)*" supported by the Energy in Buildings and Communities (EBC) Program of the International Energy Agency (IEA). IEA EBC Annex 87 is organized into five Subtasks: fundamentals (A), technologies (B), control and integration (C), performance evaluation (D), and policy & market actions (E). This systematic review, developed under Subtask A, offers a distinctive perspective by examining PECS through the lens of user experience and human performance outcomes, specifically within the thermal and IAQ domains. Complementary papers from other Subtasks examine technologies (Subtask B), control strategies (Subtask C), and evaluation methods and standardizing KPIs in [42] (Subtask D), together providing a comprehensive and coordinated overview of PECS research and practical applications. As definitions and frameworks for visual and acoustic PECS are still emerging and less developed than those for thermal and IAQ domains, they are not included in this work and are addressed in separate review works, such as [43].

2. Methodology

2.1. Selection of papers and review

A systematic literature review search was conducted in April-May 2023 using the databases Scopus, Taylor & Francis, PubMed, Google Scholar, and Web of Science. Initially, both peer-reviewed journal publications and conference papers published in English were considered. The search targeted titles, abstracts, and keywords, with the search query developed to reflect our focus on specific *space types, user categories, levels of personalization, equipment types*, and *functionality*. Following an initial application of the query, additional keywords relevant to comfort studies, such as *comfort* and *quality*, were incorporated to refine the search scope. The wildcard symbol (*) was utilized within the query to capture term variations stemming from a shared root. Specific words used were the following:

- *Space type*: (room) OR (build*) OR (built*) OR (indoor) OR (home) OR (school) OR (office) OR (work*) OR (residen*) OR (hospital) OR (car) OR (auto*)
- *User type*: (occupant) OR (human) OR (user)
- *Level of personalization*: (personal*) OR (individual) OR (local*)
- *Equipment type*: (system*) OR (device*) OR (hvac) OR (heating) OR (cooling)
- *Functionality*: (heating) OR (cooling) OR (ventilation) OR (condition*)
- *Comfort relevance*: (comfort) OR (quality)

This review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [44], with a flow diagram for screening and review phases shown in Fig. 1. After automatically removing duplicates, the selection was refined during the screening phase by applying three eligibility criteria: (i) studies unrelated to PECS (Reason 1), (ii) duplicate records (Reason 2), and (iii) review papers (Reason 3). To eliminate the papers during the screening phase according to Reason 1, the following preliminary definition of PECS was adopted: "*PECS, related to thermal and IAQ, refers to a system with the functions of heating, cooling, ventilation which is designed to control the local climate conditions of the occupant by their preference instead of conditioning an entire room and/or affecting neighboring occupants*". Later, during the review phase, the definition of PECS applied was the one officially proposed by the IEA EBC Annex 87 as follows: "*A Personalized Environmental Control System (PECS) is a*

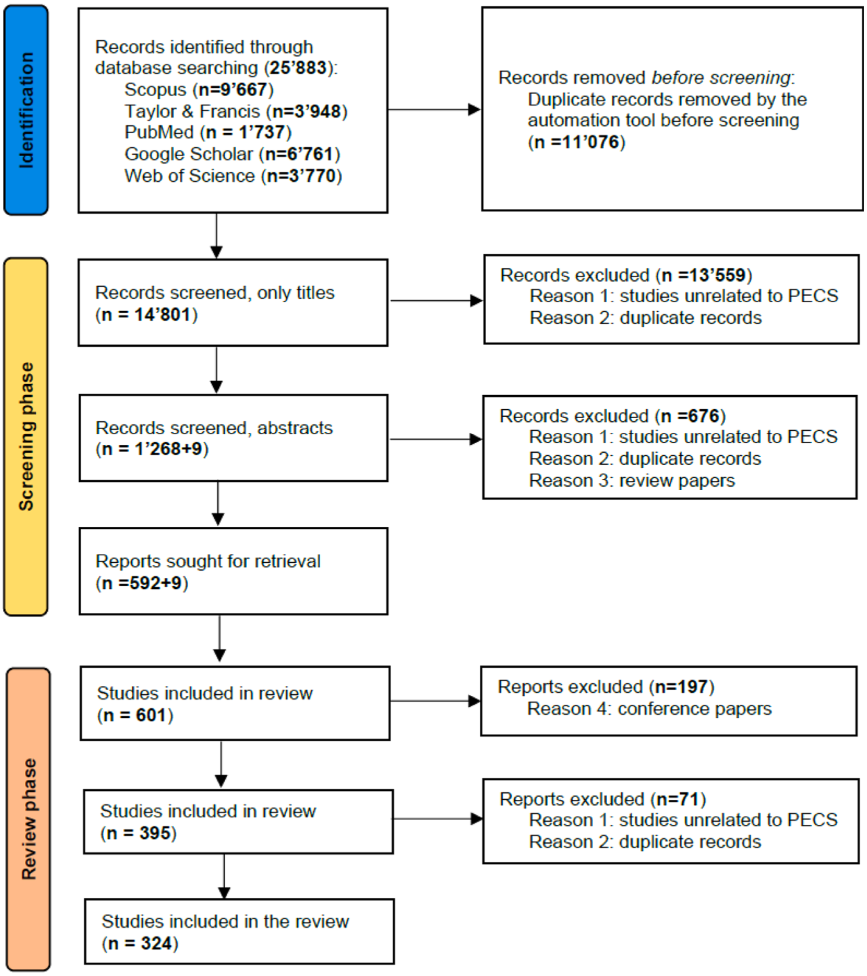


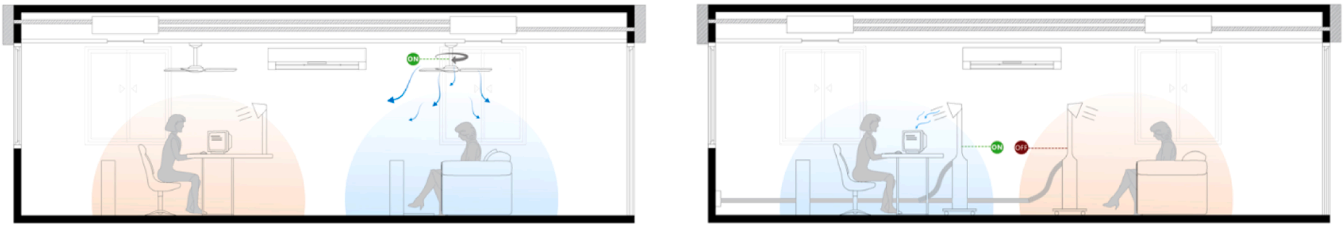
Fig. 1. PRISMA flow diagram for the systematic review of papers on PECS related to thermal and IAQ domains.

system that provides individually controlled thermal, air quality, acoustic, or luminous environments in the immediate surroundings of an occupant, without directly affecting the entire space or other occupants' environments". Although the original studies use various terms such as personal comfort systems (PCS) and task/ambient air conditioning (TAC), this review refers to all of them as PECS.

Title pre-screening reduced the dataset to 1'268 potentially relevant publications, with nine more added through snowballing, totaling 1'277. Abstract screening narrowed this to 592 studies, followed by a quality re-check that added nine more, resulting in 601 records for full-text review. Conference papers were later excluded due to limited methodological detail, though this may restrict insights into emerging technologies. Final screening removed remaining irrelevant and duplicate entries, yielding 324 journal publications focused on thermal and air quality environments. The information extracted from the 324 original papers during the review phase was organized into the following categories: publication details, study details, PECS details, background system information during PECS testing, participant details, methodological details, an overview of measured personalized parameters, subjective measurements, reference condition details, and a summary of findings. The focus domain of papers was classified into 3 groups: (i) "Thermal" (studies focusing exclusively on thermal conditions); (ii) "IAQ" (studies focusing exclusively on air quality conditions); (iii) "Thermal+IAQ" (studies considering thermal conditions with indoor air quality). Consistently with the convention developed within IEA EBC Annex 87, the PECS devices were categorized into 5 groups per mobility type (e.g., deployment approach): (i) *building attached* (attached to the building and immobile), (ii) *building semi-detached* (mobile but requires connection to the building by ducts or pipes), (iii) *building detached* (mobile and can be positioned freely in a room), (iv) *wearables* (attached to the human body), and (v) *others* (related to applications beyond buildings, e.g., vehicles, aircrafts). Additionally, the functionality for thermal management of PECS was categorized into three types: heating only, cooling only, and heating+cooling (dual management). The functionality for IAQ management of IAQ-related PECS was categorized into outdoor air supply (OAS), air treatment (AT), and the combination of the two (OAS+AT). Fig. 2 illustrates examples of PECS (i)-(iv) commonly applicable in buildings. Human involvement in the studies was categorized as participation of actual humans, use of manikins, use of human numerical models (i.e., virtual thermal manikins), or no subject involvement. Study types were categorized based on the level of control over environmental conditions and human behavior: climatic chamber studies (fully controlled), laboratory studies (semi-controlled), mixed studies (combining controlled and semi-controlled elements), field studies (conducted under real-life conditions), and simulations (virtual studies). Finally, to evaluate the effect of PECS, the question "*Did PECS provide a better, worse, or the same environment compared to the reference condition?*" was posed during the review with regards to the results of both thermal and IAQ-related studies, and responses were categorized as "better," "circumstantial," "same," or "worse." *A reference condition* refers to a condition without PECS, which serves as the control condition to show the improvement provided by installing or operating a PECS.

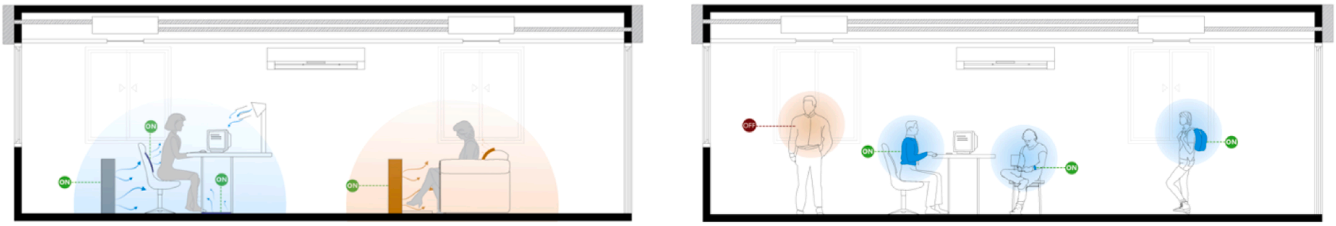
2.2. Analysis and reporting results

During the analysis phase, the papers underwent filtering and analysis to assess the benefits of PECS concerning thermal comfort, indoor air quality, health, and human performance (i.e., cognitive performance and productivity). For thermal comfort analysis, only studies involving human participants were considered to directly assess the influence of PECS on the perception of people, excluding simulations and thermal manikin experiments. Analyses were performed in terms of findings based on thermal sensation vote (TSV), thermal acceptability vote (TAV), and thermal comfort vote (TCV). Additionally, the types of scales used for the above-mentioned subjective evaluation (without distinguishing between the format of scales), the investigated local body parts when applicable, the air temperatures in which the studies were carried out, and the PECS design were extracted. Studies that reported an improvement in either TSV, TAV, or TCV were selected for further analysis. Due to inconsistency in the types of scales used for subjective evaluation, the findings were qualitatively assessed. For the IAQ domain, both simulation and experimental studies were included. Given that multiple types of KPIs were used (personal exposure effectiveness, ventilation effectiveness, contaminant removal effectiveness, intake fraction) for different study designs (i.e., different background HVAC and operation, pollution sources, location and strength, lack of standardized evaluation locations of said KPIs), cross-comparability among studies was not straight-forward. Thus, similarly to thermal comfort, the objective and subjective IAQ impact of PECS were qualitatively assessed.



(a) building attached

(b) building semi-detached



(c) building detached

(d) wearables

Fig. 2. Illustration of the building-related PECS (thermal and IAQ) classified per mobility type: (a) building attached (e.g., ceiling fan), (b) building semi-detached (e.g., personalized ventilation with fresh air supply using the building system), (c) building detached (e.g., portable heater/cooler, backrest cover, floor mat, desktop-mounted personalized ventilation), (c) wearables (e.g., heated/cooled garment, wristbands, backpacks). The microenvironment around the person is depicted using colored bubbles (blue – cool, red– warm); "ON/OFF" labels indicate whether PECS are active or inactive; arrows indicate the direction of cooling (blue) and heating (red).

Studies addressing the effect of PECS on Sick Building Syndrome (SBS) symptoms, heat stress, and human performance were relatively limited. Therefore, their findings were qualitatively summarized. Health-related benefits were evaluated based on physiological measures, reported SBS symptoms, and reductions in heat stress. Human performance-related findings encompass self-assessed performance, objective measures of work or cognitive performance, and psychological effects such as mood and motivation.

3. Results

3.1. General overview of selected papers

To illustrate how the papers selected for this review differ from previous studies, Fig. 3 presents an UpSet plot highlighting references shared among 26 earlier PECS reviews [8,11–13,20–22,24–40,45,46]. The references included in this work are listed in Appendix A (Table 1). The horizontal bars in Fig. 3 indicate the number of citations included in each review, while the vertical bars show how many references are shared among one or more of those reviews. A single black dot at the intersection of vertical and horizontal bars indicates that the associated references appeared in only one review, whereas a vertical line connecting multiple dots shows that certain references were shared across multiple reviews, with the dots' positions corresponding to the specific reviews involved. The most significant overlap is with Liu et al. [40], who share 21 references with this study, followed by Rawal et al. [28], André et al. [39], and Song et al. [30], each sharing only six references. Other studies share fewer than four references. These results underscore the comprehensive scope and broader thematic focus of this review.

The historical overview of publications selected for this review is shown in Fig. 4. Interest in thermal and IAQ-related PECS has grown steadily over the decades, peaking in 2018, followed by a slight decline over the next three years before rebounding in 2022. The earliest record dates to 1988, while data for 2023 is incomplete, as this review only includes publications up to May 2023. Despite being incomplete, the 2023 data, with 36 publications, already exceeds the number of papers published in 2022. Historically, research on PECS has predominantly focused on the "Thermal" domain, and studies involving human participants were the most prevalent. The geographical distribution of the PECS studies is shown in Appendix A (Fig. 14).

The Sankey diagram shown in Fig. 5 further illustrates the distribution of studies across environmental domains, human involvement (e.g., humans, manikins, human numerical models, no subject), test environment type (e.g., controlled experiments in climatic chambers, simulations, mixed studies, lab studies, and field studies), mobility type (e.g., building attached, wearables, etc.), and application fields, highlighting their interconnections. Studies focusing on the “Thermal” domain dominate the research, while those focusing on “Indoor Air Quality (IAQ)” alone represent a minor portion. A combination of both domains, referred to as “Thermal+IAQ,” is considered in nearly 1/5 of publications. Regarding test types, climatic chamber experiments were the most common, followed by simulations; testing PECS in more realistic environments, such as living lab studies and field studies, is limited. Simulation studies were mainly conducted with computational fluid dynamics (CFD), using human numerical models (i.e., virtual thermal manikins). Regarding PECS mobility type (i.e., deployment), most were building-detached, followed by semi-dettached, wearables, and building attached. The designs related to car and airplane settings (category

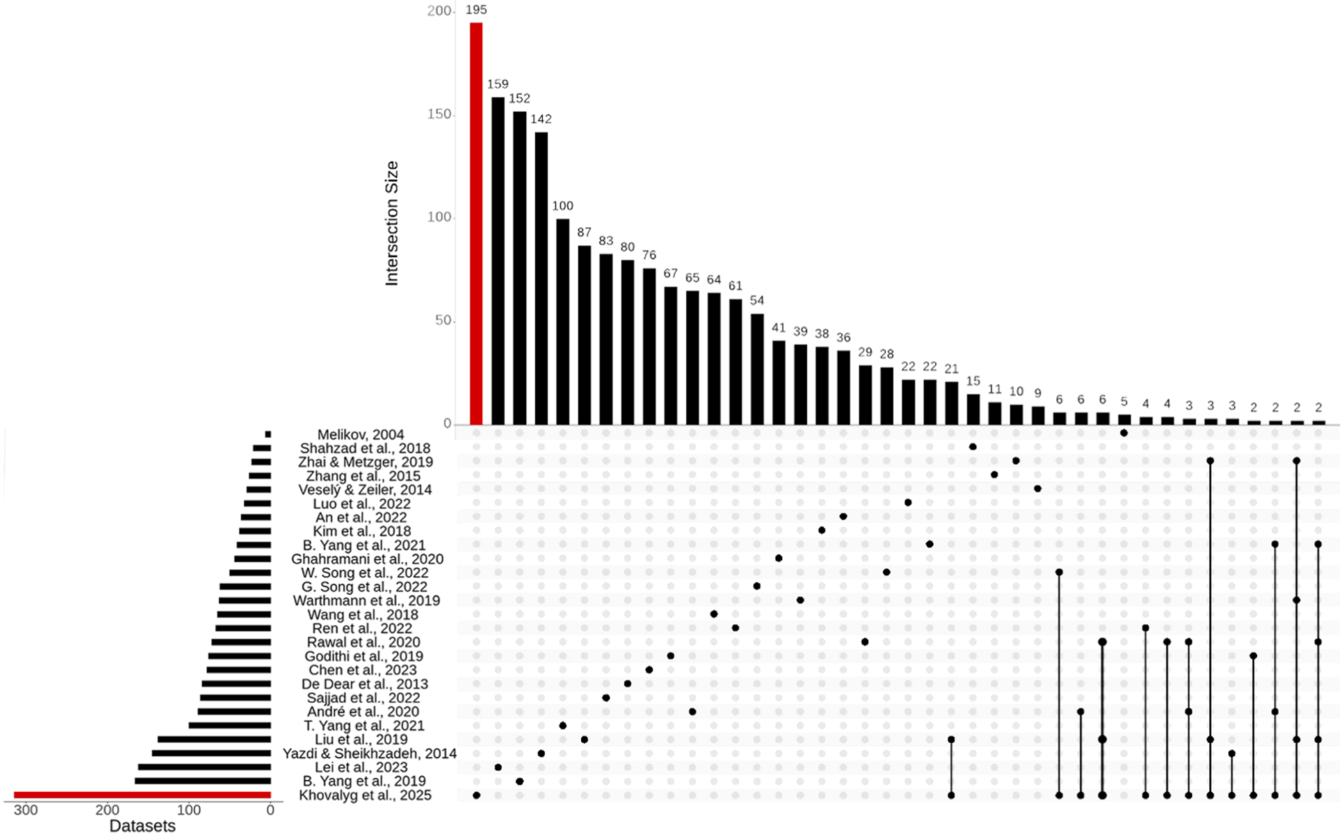


Fig. 3. Overview of shared references of this work and the previous review papers [8,11–13,20–22,24–40,45,46] (horizontal bars - number of citations each review paper included in their analysis, vertical bars - number of citations shared among one or more reviews). The plot was generated using the R programming language with the UpsetR package [47].

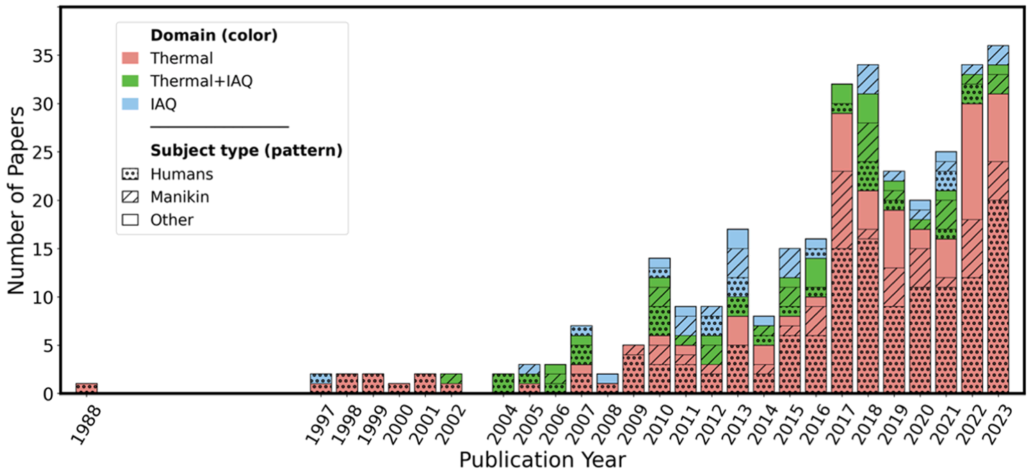


Fig. 4. Distribution of the papers per publication year according to the focus domains and subject type ("other" refers to human numerical models and cases with no subjects).

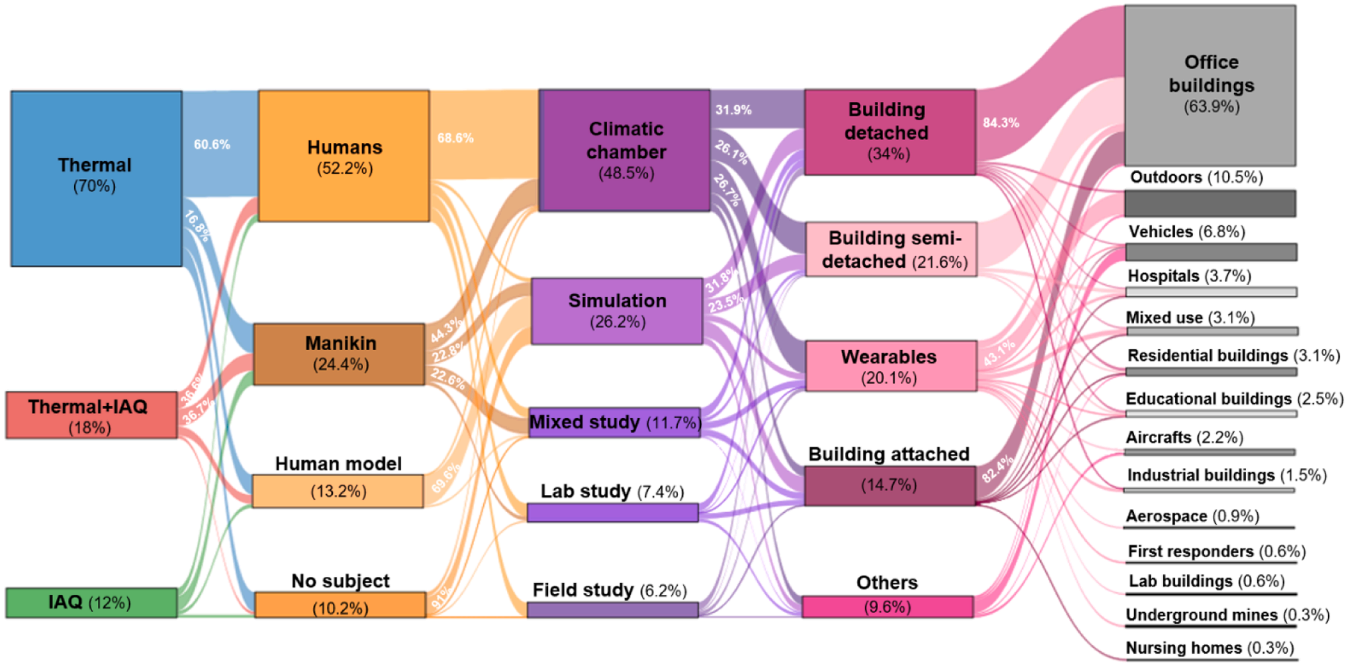


Fig. 5. Diagram detailing the distribution of studies per different domains, human involvement, study types, PECS mobility, and application fields.

"others") appear the least frequently. Office buildings were the primary application field for PECS, with outdoor environments being the second most common. Various other applications accounted for less than 25 %.

3.2. Comfort benefits of thermal PECS

3.2.1. General overview of thermal PECS

Based on the 133 studies [17,18,31,48–177] on PECS related to the "Thermal" domain and 22 studies [178–199] on combined "Thermal+IAQ" domains concerning only humans, the diagram in Fig. 6(a) overviews the distribution of 197 thermal PECS entries (i.e., individual PECS tests) per mobility classification versus thermal functionality Fig. 6. The largest group consists of *building detached devices*, which are used for both heating (42 %) and cooling (44 %) in roughly equal proportions. The next largest category is *wearables*, mainly used for cooling (69 %) and less frequently for heating (24 %). *Building semi-detached devices* are primarily used for cooling (78 %), with a smaller portion serving both heating and cooling needs (19 %). The smallest category, *building-attached devices*, is predominantly used for cooling (86 %). The "*others*" category is the second least common, with an equal share of devices used for heating and cooling. Across all categories, the share of devices capable of both heating and cooling is relatively small, with a maximum of 19 %. Fig. 6(b) shows the number of reported PECS, grouped by whether they can provide *a better thermal environment* compared to a reference condition without PECS. A PECS was classified as providing a "*better*" thermal environment when TSV shifted towards *neutral*, TAV or TCV improved, or when physiological strain was reduced. When both better and worse results were reported, e.g., depending on room temperature, these PECS were classified as having "*circumstantial*" benefits. When the PECS was not compared against a reference condition, it was classified as "no comparison". The primary objectives of such studies were to compare different operations of a PECS or to compare it with other devices. The "*worse*" results reported in the papers were often linked to tests where conditions were set by the experimenter rather than by the occupants themselves. The results in Fig. 6(b) show that the PECS reported in the selected studies were

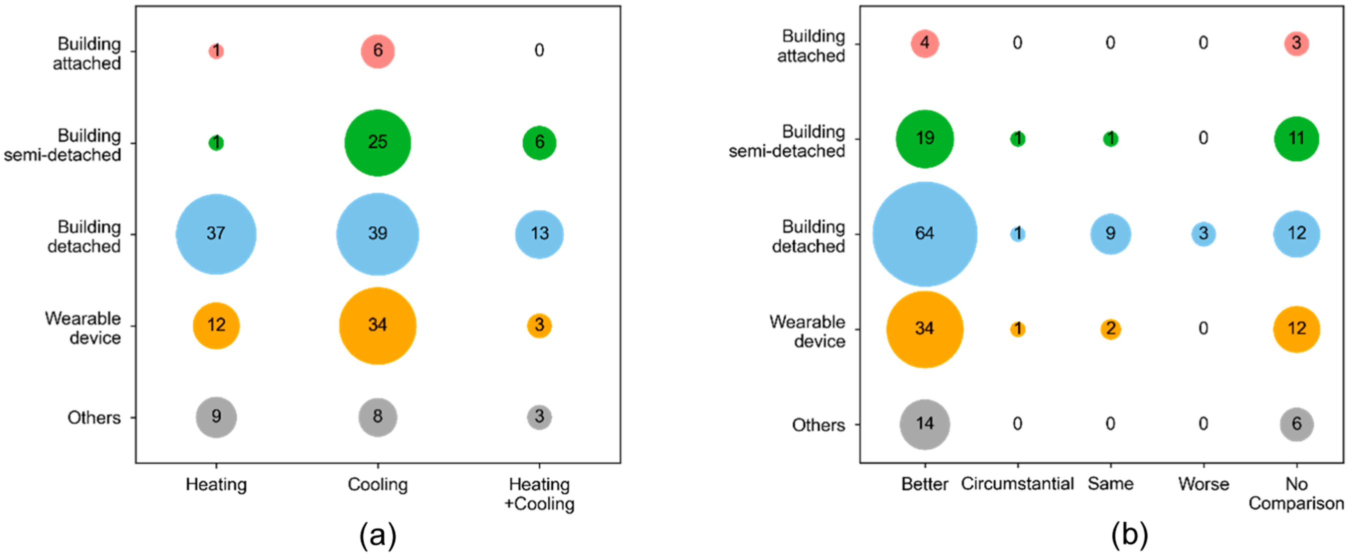


Fig. 6. Overview of the reported PECS related to thermal domain: (a) distribution per classes (mobility vs. thermal functionality), (b) comparison of whether PECS can provide a better thermal comfort compared to a reference scenario without PECS.

skewed towards either “*better*” (69 %) or “*no comparison*” (22 %). A summary of the studies, categorized by their effect on thermal comfort and PECS mobility types, is provided in Appendix A (Table 2).

Fig. 7 shows the trend of background air temperature investigated for different types of PECS, focusing on those that provide a *better* thermal environment. The investigated air temperature was binned in 2 K intervals. When multiple temperatures were tested for a single PECS, each temperature was counted as a separate occurrence. Most of these occurrences fell within 13-33 °C, reflecting the PECS’s ability to extend the background setpoint temperature of indoor spaces without compromising occupants’ comfort. Heating solutions were commonly tested at 17–19 °C, and cooling solutions were commonly tested within a broader range of 23–33 °C. While there was more diversity in the type of PECS in cooling conditions, building detached devices were predominantly used for heating. In terms of functionality, most PECS devices were explicitly developed for either heating or cooling. Those that serve both functions, such as chairs, were primarily reported in moderate temperature ranges of 18–28 °C. Studies involving temperatures outside the 13–33 °C range primarily assumed outdoor conditions or vehicles exposed to extreme environments. In these conditions, either wearable devices such as vests or building detached, conduction-based devices such as cushions and mats were studied.

The design of PECS devices that provide a *better* thermal environment is shown in Fig. 8. When multiple PECS were combined and used at the same time, as in [53,91,92,184], they were classified as “*Combined PECS*.” Studies reporting building-attached devices were limited, and those reported were ceiling fans (e.g., [49,50]), air nozzles attached to the ceiling, or individually controlled localized active chilled beam (e.g., [199]). Configurations of ceiling fans that fall under the definition of PECS (i.e., those that offer personal control without directly affecting the entire space or other occupants) are taken into account. For *building semi-detached PECS*, nearly all occurrences were a type of PV (e.g., [152,153,200]) or a combination of a PV with supplementary heating or cooling devices, such as chairs (e.g., [184]) and radiant panels (e.g, [181]). Hydronic radiant panels, such as in [56] implemented for both heating and cooling, are *building semi-detached*, while electric radiant panels (e.g., [86]) used solely for heating are *building detached*. Despite the wide range of configurations, the *building-detached devices* primarily

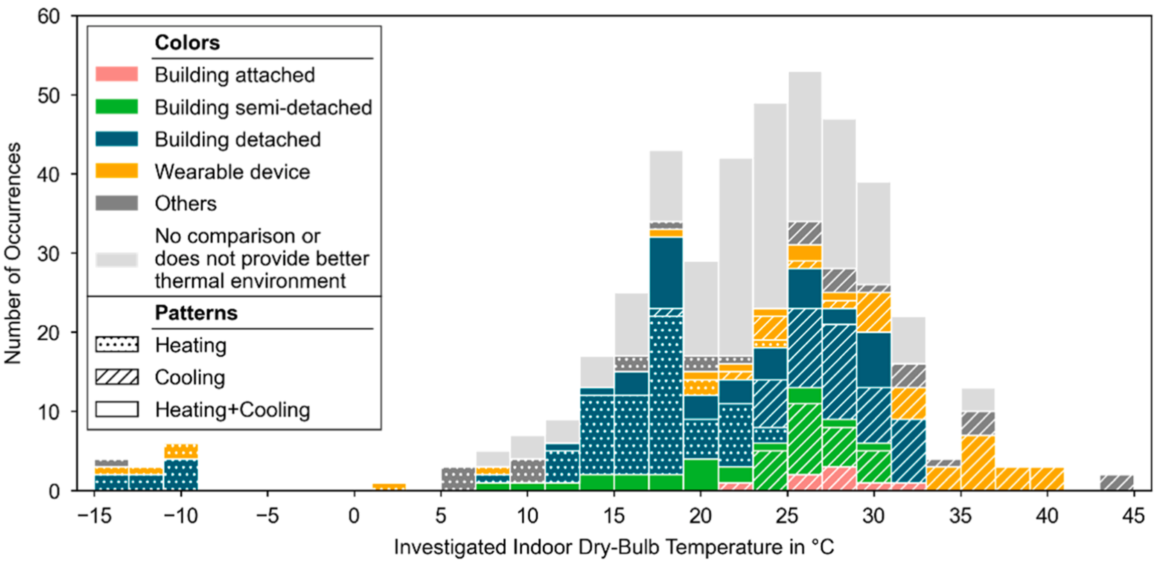


Fig. 7. Investigated air temperature per thermal PECS type.

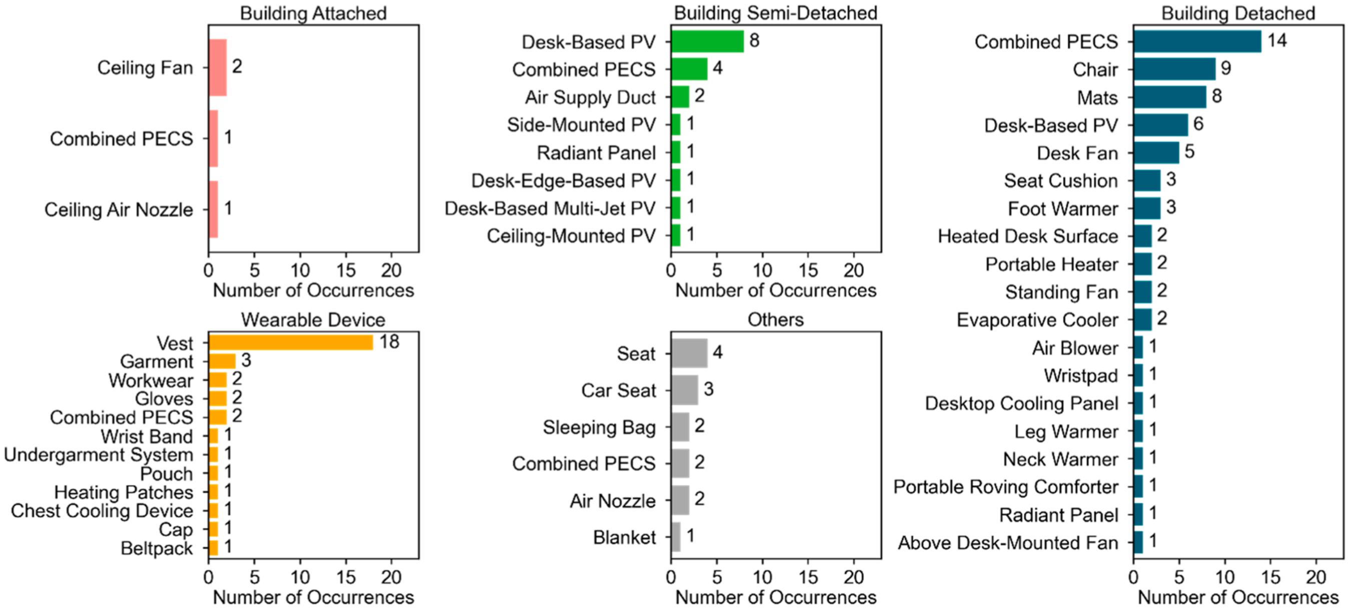


Fig. 8. Overview of the designs of PECS that provide a better thermal environment.

included chairs (e.g., [61,68,87]), cushions (e.g., [65,73]), fans (e.g., [69,163]), personalized ventilation (PV) systems (e.g., [188,201]]), and surface temperature-controlled elements such as mats (e.g., [74,79]), panels (e.g., [78]), or desks (e.g., [90,92]). *A building-detached PV* (e.g., [85]) refers to a ductless system that draws conditioned air from a diffuse ventilation source via an intake located at floor level. Heated mats were placed either on the floor [62,74,79,93,94] or on the table [60,138,139]. Vests - ventilated [97,102,107,158], hydronic [48,96,117], or PCM packets [107,111] - were the most common wearable devices, including the combined PECS solutions (e.g., [122,142]). For PECS devices, such as in [125,129,132], classified as "*others*" (i.e., those developed for spaces other than typical indoor spaces), conduction was also the most dominant heat transfer mode.

3.2.2. Overview of thermal sensation, comfort, and acceptability improvements

The studies categorized as *better* evaluated the benefits of thermal PECS using various subjective metrics, including thermal sensation (TS), thermal comfort (TC), and thermal acceptability (TA). Appendix B summarizes the different scales used for these assessments and their frequency, highlighting inconsistencies in scale types. The choice of scale can influence survey responses, making it difficult to standardize results across studies; consequently, the literature review's findings on thermal sensation, comfort, and acceptability were assessed qualitatively.

- **Thermal Sensation:** Studies on building-attached PECS, such as ceiling fans, consistently show improved whole-body and local thermal sensation, with TSVs shifting toward neutrality. For example, He et al. [50] found that ceiling fan users reached thermal neutrality 5–10 minutes sooner and felt ~0.5 units cooler, even at slightly higher ambient temperatures. Semi-detached PECS like desk-based personalized ventilation (PV) also enhanced thermal comfort, with TSV improvements of –0.3 to –0.4 units at 27–29 °C, especially when users could control airflow [187]. Detached PECS, including heated/cooled chairs, cushions, and desk fans, similarly improved thermal comfort. Luo et al. [68] reported reductions in warm discomfort by 1.8 and cold discomfort by 1.2 TSV points, with greater local benefits. He et al. [67] found similar effects using a heated chair and leg warmer. Tang et al. [73] showed that desk and pedestal fans improved thermal sensation by about 1 TSV unit.
- **Thermal Comfort:** Among the 28 % of studies reporting TCV before and after using PECS, 64 % show improved outcomes, 21 % report circumstantial improvements, 11 % show no change, and 4 % report worse outcomes. Overall, PECS can often enhance thermal comfort, though effectiveness depends on ambient conditions and device performance. Building-detached PECS (e.g., heated/cooled chairs) show the most consistent benefits: 70 % report improved TCV, 12 % circumstantial, 10 % no change, and 6 % worse outcomes. Luo et al. [68] found a 1.7-point whole-body TCV improvement in both heating and cooling, with local gains at the face (cooling) and foot (heating). Semi-detached PECS (e.g., desk-mounted PV) have 50 % better TCV outcomes, 21 % circumstantial, 14 % unchanged, and 7 % worse. Yang et al. [55] observed significant TCV improvements at 25–29 °C with user-controlled PV, most notably at 29 °C (~1-point increase, $p < 0.001$). Wearable PECS (e.g., wrist-worn devices) show 58 % better outcomes, 31 % circumstantial, 8 % unchanged, and 4 % worse, reflecting limited capacity and sensitivity to environmental context. Due to the small sample size ($n = 7$), building-attached PECS (e.g., ceiling fans) were not analyzed separately. Still, He et al. [50] reported 80–90 % comfort votes under most tested conditions.
- **Thermal Acceptability:** The use of PECS consistently improves thermal acceptability in indoor environments, often exceeding the 80 % threshold set by comfort standards and sometimes reaching 100 %, especially when users have control over the device. Across all PECS types, thermal acceptability increases significantly. For building-attached PECS, such as ceiling fans, user control leads to nearly 100 % acceptability, especially at higher temperatures [50]. Semi-detached PECS also perform well when personalized. Yang et al. [52] found over 88 % acceptability at 26–28 °C with user-controlled airflow, but it dropped to 31 % at 30 °C without control. Similarly, personal control increased acceptability from 0 % to 63 % at 14 °C, 38 % to 88 % at 16 °C, and up to 100 % at 18–20 °C [53]. Detached PECS showed varying results based on device type and combinations. Combining devices boosted acceptability to over 80 % in both cold and hot conditions [68]. For instance, a heated chair alone improved acceptability at 16 °C, but at 14 °C, combining it with a leg warmer was necessary to exceed 80 % [71]. In warm conditions, desk fans and ventilated cushions raised acceptability above 90 % at 28 °C but fell short at 30 °C [67]. Notably, participants who lacked but desired PECS reported lower acceptability than those who either had or didn't want them [202]. Wearable PECS also

enhanced comfort. Ventilated clothing raised acceptability by ∼20 % at 28–30 °C and over 30 % at 32 °C [203]. Comparisons between PECS types yielded mixed results: the study [159] found heated jackets to be more acceptable than radiant panels and heated chairs, while the study [158] found no difference between air-ventilated clothing and desk fans, although both performed better at 30 °C than at 28 °C or 32 °C.

3.3. Benefits of PECS targeting indoor air quality

3.3.1. General overview of IAQ-related PECS

This overview includes 135 individual PECS tests from 98 papers. Appendix A (Table 3) summarizes the studies by their impact on IAQ, grouped by PECS mobility types. Fig. 9(a) shows the distribution of PECS by mobility classification and IAQ functionality. IAQ functionality refers to how PECS manages IAQ: through outdoor air supply (OAS), air treatment (AT), or both (OAS+AT). OAS dilutes contaminants in the breathing zone while AT involves filtration, irradiation or local exhaust, to clean or prevent the spread of polluted air. OAS+AT combines both approaches, including the filtration of the outdoor air in the air handling unit. Most experimental studies fall in this group. Simulation studies assuming zero particle concentration at the PECS inlet were also classified as OAS+AT. OAS and OAS+AT were more commonly used compared to AT. The number of PECS relying solely on AT was limited and were either air recirculation with HEPA filters [204,205] or localized exhaust [206–208]. Fig. 9(b) shows the number of reported PECS, grouped by whether they can provide *better* indoor air quality compared to a reference condition without PECS.

Half showed that PECS provided *better IAQ* compared to a reference case with no PECS, and the other half did not have a reference. The largest group consists of *building semi-detached devices* (73 %), followed by *building attached* (8 %) and *building detached* (6 %). *Wearables* and *other* devices constitute only 13 %. The PECS design providing *better IAQ* is shown in Fig. 10. *Building semi-detached* desk-based PVs (e.g., in [205, 209–211]) was the most studied PECS. *Building detached* desk-based (e.g., in [212–214]) and seat-based (e.g., in [215]) personalized ventilation (PV) relied on air supplied from the room displacement ventilation system as a source for clean air. *Building attached PECS* were all overhead localized ventilation systems (e.g., in [216,217]), in some cases assisted with chair or desk fans (e.g., in [209,217]). While being classified on their own as detached PECS, the chair and desk fans mentioned in this categorization were used as assistive secondary devices aiding in stabilizing the primary PV jets by pulling them towards the breathing zone of the occupant. Thus, their categorization followed the primary PECS (i.e., overhead personalized ventilation).

3.3.2. Overview of IAQ performance

The 98 studies assessing PECS and IAQ, focus mostly on PV. Using CFD simulations or experiments with thermal manikins or human subjects (for subjective evaluation), they examine how PECS affects the inhaled air quality at the breathing zone. Various KPIs and metrics assess changes in exposure to non-infectious pollutants (e.g., tracer gas) and infectious aerosols from indoor sources. These studies explore how indoor parameters influence PECS performance and its implications on design, operation, and spatial layouts in offices, hospitals, aircraft cabins, and vehicles. Performance is consistently benchmarked against a reference case using a standalone total volume system with equivalent air change rates. The studies examined various factors affecting PECS performance, including PV design aspects (e.g., air terminal device shape, size, placement, and supply conditions), interactions with different background HVAC systems (e.g., mixing, displacement, or radiant systems), and integration with assistive devices like desk fans or personalized exhaust. They also assessed the effects of background and supply air temperatures, pollutant source location and intensity, occupant differences in response to airflow rates, relative seating positions, and disturbances caused by occupant movement or posture changes.

PV has consistently shown IAQ improvement in the breathing zone. Wearable PV (headsets and seat-integrated nozzles), positioned within a few centimeters of the breathing zone, supplying as low as 0.2 l/s, achieve up to 60 % improvement in personal exposure effectiveness (*PEE – amount of clean PV air being inhaled)* compared to cases without PV [218]. In contrast, a desk-mounted PV situated 80 cm from the user requires a supply rate of 20 l/s to achieve the same level of *PEE.* At such close distances, the clean PV air is directly inhaled with minimal mixing between the PV jet and the background. Therefore, the IAQ performance of wearable PV surpasses that of desk-mounted (30-80 cm from the breathing zone) [184,196,204,219,220] and ceiling-mounted PVs (>1 m from the breathing zone) [221]. The lowest improvement was noted for PV located at 1 m from the user (e.g., ceiling PV), due to greater entrainment of background polluted air (e.g., only 20 % improvement in PEE at 10 l/s). This is lower than the *PEE* achieved by all desk-mounted PV for the same flow rate.

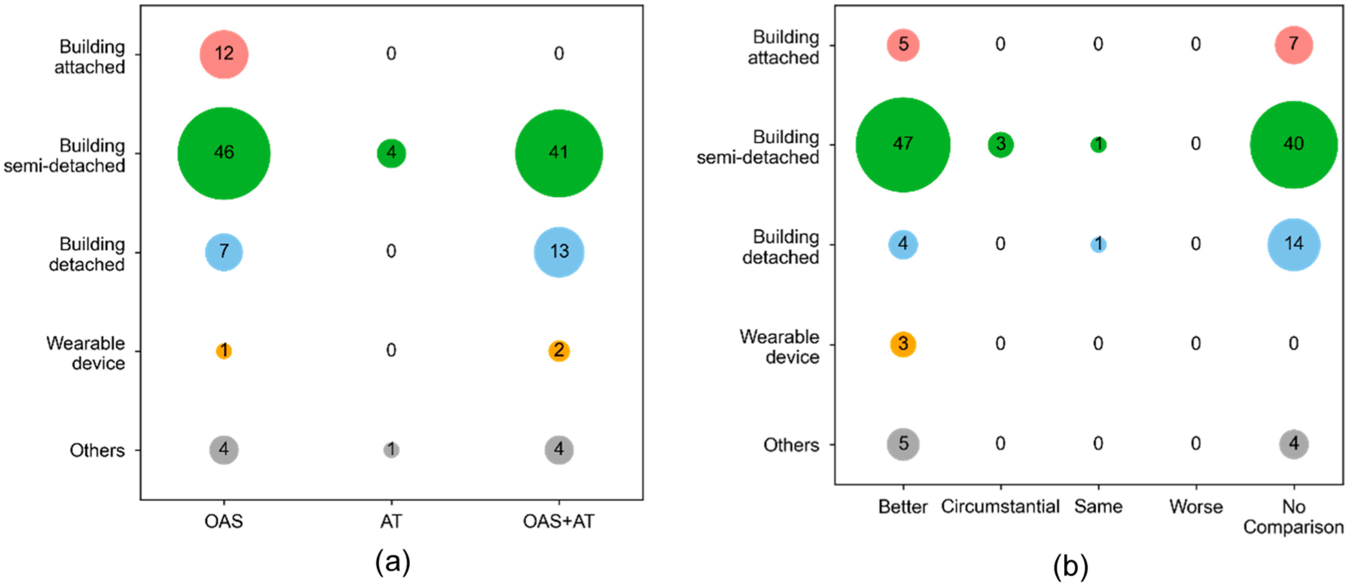


Fig. 9. Overview of the reported PECS related to the IAQ domain: (a) distribution per IAQ management (OAS: outdoor air supply, AT: Air treatment), (b) comparison of whether PECS can provide a better IAQ compared to a reference scenario without PECS.

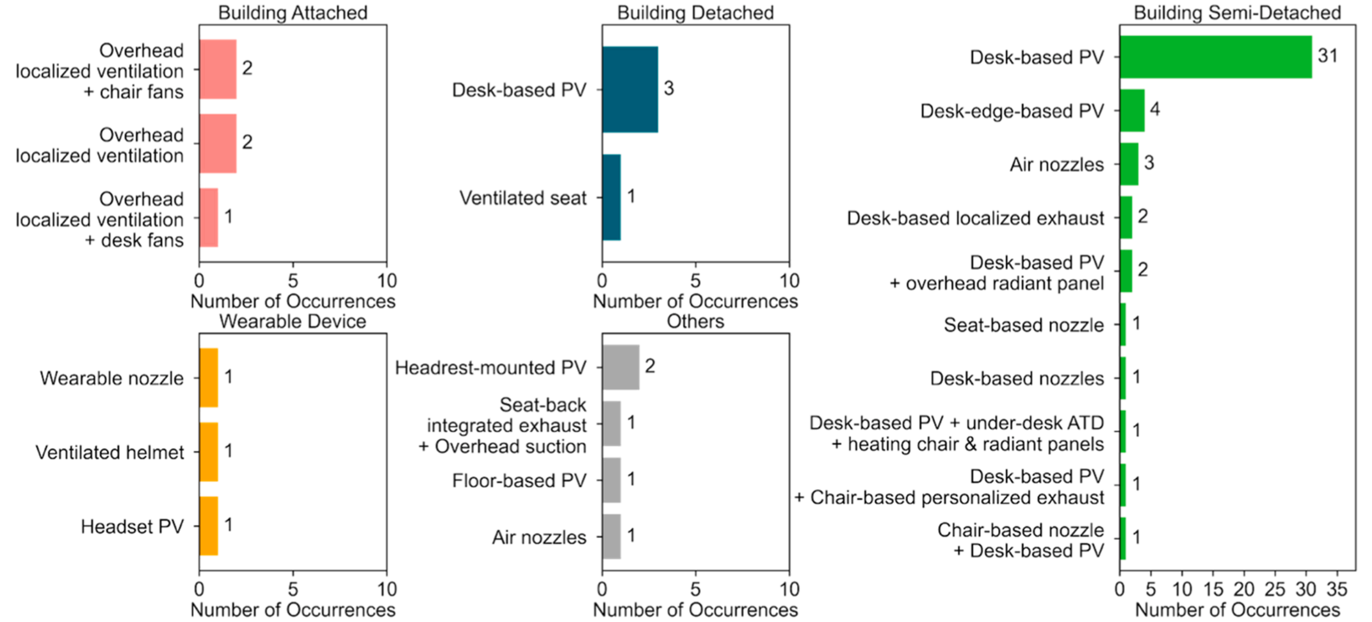


Fig. 10. Overview of the designs of PECS that provide a better indoor air quality.

PE can strengthen and guide the PV jet core [222–224]. It effectively penetrates the occupants' rising convective boundary layer and exhaled air to deliver clean air. Thus, PE can enhance PV IAQ performance. Chair or desk fans can perform the same function as PE [206,207,225]. The only difference is their mobility. While PE is ducted and building semi-detached or attached, chair fans are detachable. Adding an assistive device results in approximately a 10-20 % increase in the achieved *PEE* of all PV having the same design. For example, chair fans were able to enhance the performance of building-attached ceiling PV by 20 %. Assisted PECS can perform better than standalone PECS in the same distance from the BZ at even lower PV flow rates. However, this does not imply an improvement in energy performance given the additional operation of PE fans. The PE flow rate of PE influences the *PEE*. If it exceeds that of the PV, it can result in a deteriorated performance. For example, at 10 l/s, a PV associated with a PE at 10 l/s resulted in a *PEE* of 40-50 %, while that at 20 l/s resulted in a *PEE* of 10 %. Consequently, the use of assistive devices needs to be carefully designed.

The improvement of Perceived Air Quality (PAQ) through PECS was a substantial area of research, with 20 papers identified in this review [72,84–86,133,153,182–184,186,187,189,190,193,195,198,226–229]. Reported benefits ranged from 15 % to 60 % decrease in the share of occupants dissatisfied with PAQ, or the equivalent of feeling the air ≈ 2–4 K "cooler" without actually lowering the room temperature, which improved perception of air freshness. One of the key findings is that increased air movement, associated with PECS, significantly enhances PAQ [86,182,186,190,226]. For instance, the introduction of air movement at a velocity of 1 m/s at the breathing zone was found to elevate PAQ to levels comparable to those in cooler and neutral conditions [86]. This improvement is attributed to the disruption of the thermal plume around the body and the association of air movement with outdoor breezes, which are typically perceived as "fresh". Higher face-level air velocity systematically improved freshness scores, especially when the room air was warm, humid, or polluted [226,227]. The most beneficial is the supply of personalized air that is cool, dry, and non-polluted. Delivering air warmer than room temperature would result in a decrease in PAQ [133]. Furthermore, the use of PV has been shown to improve PAQ by providing clean, cool air directly to occupants, confirming the results of tracer gas and CFD studies. This approach also reduces the intensity of Sick Building Syndrome symptoms [186]. However, those benefits rely on the personalized airstream being at least as clean as room supply – recirculated, polluted local air will not deliver the same PAQ and health improvements [190,226].

3.4. Health Benefits of PECS

According to the World Health Organization (WHO), health is defined as "*a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity*" [230]. Here, we refer to this definition to analyze the health benefits of PECS in terms of both non-clinical and clinical symptoms. Non-clinical health symptoms are often grouped under the Sick Building Syndrome (SBS) umbrella. While no universally accepted clinical definition of SBS exists, and objective physiological abnormalities are generally absent in patients with SBS symptoms, SBS typically encompasses nonspecific complaints such as upper respiratory and eye irritations, headaches, fatigue, and rashes [231]. From our literature review, we could identify only 12 studies [51, 81,85,98,133,181,186,187,189,190,226,232] that systematically examined the relationship between PECS and SBS symptoms. Fig. 11(a) provides an overview of these studies (references provided in Table 4, Appendix A), comparing whether PECS improved or failed to improve SBS-related complaints. As shown, the results are not univocally positive regarding the SBS performances of PECS. A discussion of the main SBS findings from the reviewed studies, along with the various metrics and exposure times used to analyze them, is provided in Section 3.4.1. Fig. 11(b) provides an overview of whether PECSs improved or failed to improve participants' physiological state (references provided in Table 4, Appendix A). Most reviewed studies perform only one unique physiological measure (Fig. 12a). The most commonly used physiological or clinical measures to assess benefits of PECS, as depicted in Fig. 12 (b), can be categorized as follows: body temperature metrics (e.g., skin temperature and core temperature), cardiovascular response metrics (e.g., heart rate, heart rate variability, and blood pressure), and metabolic response metrics (e.g., energy expenditure and heat losses/gains). The studies focusing on the thermal domain employ these physiological metrics more often than IAQ studies (Fig. 12b), and the skin temperature is the most assessed physiological parameter. Most of the studies that consider the human physiological state focus on moderate environmental conditions. To better analyze the health benefits of PECS in clinical terms, we discuss in Section 3.4.2 only those PECS studies investigating heat stress conditions characterized by air temperatures of 35 °C or higher, such as [48,96,102,104,106,120,177].

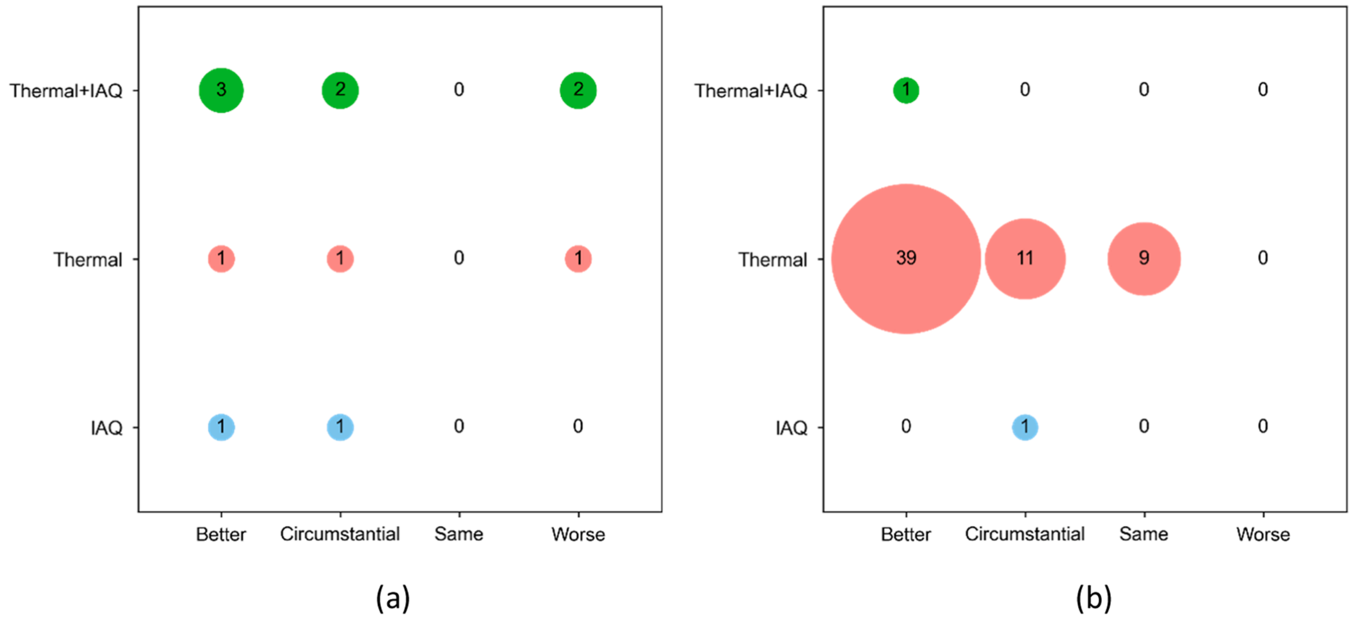


Fig. 11. The health performance of PECS compared to the reference condition (according to the focus domain of the study) for: (a) SBS symptoms, and (b) human physiological state.

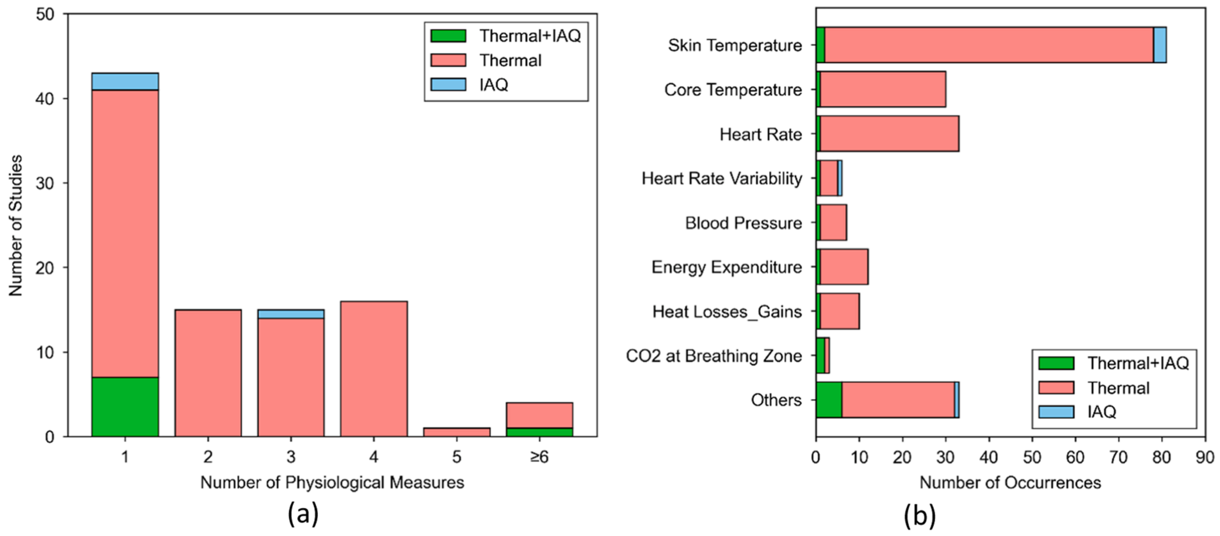


Fig. 12. Number of occurrences of studies (based on the focus domain of the study) according to (a) the number of physiological measures in PECS studies, and (b) the type of physiological measures.

3.4.1. *SBS Symptoms*

All studies [51,81,85,98,133,181,186,187,189,190,226,232] concerning SBS symptoms used self-administered questionnaires to assess the relationship between PECSs and the intensity of SBS symptoms. Some studies used a continuous scale coded from 0 to 100 % to assess the severity of symptoms such as difficulty concentrating and thinking, severe headache, ability to work, well-being, fatigue, and dizziness [85,181,186,189,190,226]. Other studies used continuous scales with different degrees of intensity (e.g., from “*no*” = −1 to “*overwhelming*” = 1) so the participants could rate their level of irritation, comfort, or dryness of eyes, nose, throat, lips, and skin [51,81,187]. Some studies used “Yes/No” questions regarding whether symptoms such as irritation of the eyes [85,133], cold hands/feet, shivering, dizziness, eye discomfort, runny or stuffy nose, and dry throat [98] were experienced. Another study used questions about the occurrence of symptoms such as headache, fatigue, difficulty concentrating, irritation of the eyes, nose, throat, and skin, and musculoskeletal and respiratory problems [232]. Despite differences in how the questions were formulated, all studies captured recurring symptoms like upper respiratory, eye, and skin irritations, headaches, and fatigue, highlighting a common recognition of key SBS indicators. Except for Menzies et al.[232], all reviewed studies examined the human response to PECSs in a controlled laboratory environment resembling an office room. The duration of the exposure times used in the studies varied from 60 min to a maximum of 240 min. Menzies et al. [233] conducted their research in real-world office settings, with a study duration of one year. They found that under long-term use conditions, headache and irritative symptoms of the skin, eyes, nose, and throat were significantly lower among the employees who had a workstation equipped with individually controlled overhead personal ventilation (PV) compared to those without it. Given that the occurrence and severity of SBS symptoms appear to be influenced by exposure duration [133], short-term experiments lasting 60 to 140 minutes may not adequately assess the effectiveness of PECSs in reducing SBS symptoms [51,181].

The reviewed studies show that the use of PECS generally improve thermal comfort compared to no PECS conditions, but have varying impacts on health-related symptoms, particularly SBS symptoms. Some studies show no impact on SBS symptoms [81]. Others show that personal convective cooling and ventilation systems require careful airflow calibration and air velocity control to balance airflow benefits with discomfort risks, which are not only due to draught risk but also to SBS-related complaints [51,85]. Particularly in warm conditions, facially applied high air movement can increase eye dryness, headaches, eye, nose, and throat irritation, visual fatigue, and concentration over time [51,85,133,187,189]. At high air velocities, discomfort is also perceived due to the increased pressure of the airflow. In polluted environments, there is the additional risk of generating movement of polluted room air in the breathing zone of occupants [85]. Compared to mixing ventilation, the SBS symptoms, such as the intensity of headache and the ability to think clearly and to concentrate, do not improve when the supplied personalized air is recirculated with polluted room air [186,226]. However, participants generally prioritize thermal comfort over health impacts, possibly because thermal comfort effects are more immediate, and the studied exposure times are limited. Indeed, SBS symptoms are generally found to increase over time [133]. Providing individual control is essential to prevent discomfort among the most sensitive occupants [81,133,181,187,232]. Other important parameters that affect the intensity of SBS symptoms are the temperature, relative humidity, and cleanliness of the inhaled air. Personalized ventilation, which supplies clean, drier, and cooler air than room air towards the face, provides the greatest improvement in SBS symptoms [186,226]. On the contrary, personalized ventilation, which supplies warm air directly to the occupant's face, causes an increased perception of nose dryness and eye irritation [133].

3.4.2. Heat stress

In addition to SBS, heat stress is one of the most relevant and commonly studied topics related to the health benefits of PECS. Heat strain refers to the physiological and psychological responses of the body to heat stress [234]. Exposure to excessive heat can increase mortality and morbidity, affect adverse mental health, and affect pregnancy and birth outcomes [235]. Heat stress creates high-intensity thermal discomfort, pushing the body beyond its thermal allostasis, such as elevated sweating [236], cardiovascular responses [237,238], and core body temperature [239]. By delivering cooling directly to the individual's body, PECS have been shown to effectively reduce heat stress in both indoor and outdoor environments. Personal type garments [48,97,102,104,106,177] or other wearable devices like helmets [170] and T-shirts embedded with cooling modules [203]. Additionally, a few studies have explored the use of furniture-embedded air movement for cooling, such as those by Melikov et al. [190] and Zhang et al. [132]. The effects of PECSs on heat stress have been evaluated through self-reported surveys and physiological measurements, as demonstrated in various studies [48,96,97,102,104,106,120,177]. In general, the reviewed studies have shown that PECSs can significantly reduce skin temperature, sweating, and heart rate when cooling is adequately delivered, with a few exceptions reported in certain studies. For instance, a cooling vest was found to reduce mean skin temperature by 1.9 °C in [48]. Additionally, a vest with phase change material (PCM) lowered the local skin temperatures of the frontal and back torso segments by up to 5.4 °C and 4.6 °C, respectively [106]. Sweating loss was reduced by 26 % with the use of a liquid cooling garment for firefighters, while sweat evaporation efficiency increased by 11.9 % to 13.7 % [97]. Heart rates were slightly lower (89–99 bpm) with a PCM vest compared to the baseline of 105 bpm [106]. However, the effectiveness of wearable PECSs in reducing core temperature can vary depending on the intensity of heat stress and the cooling capacity of the device. Choudhary & Udayraj [97], Ni et al. [102], and Ouahrani et al. [106] reported a reduction in core temperature with wearable cooling devices, though other studies [48,96,104] observed no significant effect. Moreover, even if the cooling power of PECSs is insufficient to significantly impact physiological signals, their use can still alleviate psychological thermal discomfort and reduce negative emotions [240].

3.5. Human performance benefits of PECS

Studies evaluating human performance with PECS can be grouped into those focusing on cognitive performance, work productivity, and psychological effects such as mood and motivation. Cognitive performance primarily refers to an individual's ability to process information, think logically, recall information, and complete cognitive tasks with speed and accuracy [241]. On the other hand, productivity relates to measurable work output, efficiency, and task completion, which may or may not require intense cognitive engagement [242]. As the number of PECS studies considering human performance benefits is limited, a qualitative overview is provided.

Cognitive performance: A total of only three papers explored the effect of PECS on occupant cognitive performance, and all of them focused on thermal PECS, including a radiative footwarmer [75], standing fans [81], and a device combining PV ATD with a horizontal desk grill with a foot heating coil [53]. Su et al. [53] investigated both subjective self-evaluated work performance and cognitive performance, while Yan et al. [75] and Schiavon et al. [81] only focused on cognitive performance tests. Regarding seasons, a study [81] was conducted with fans in a summer background, and the other two [53,75] were set in a winter background. The cognitive performance tests used in these studies included choice reaction time, finger tapping, Stroop, N-Back, typing, proofreading, creative thinking, math exercises, and logical thinking. In a warm and humid climate (Singapore), the best cognitive performance was observed at 26 °C, where the presence of a fan did not enhance performance. However, increasing the temperature to 29 °C reduced performance on speed-related tests, and using a fan partially mitigated this decline [81]. In winter, the combined PECS presented in [53] significantly improved cognitive performance, including self-evaluated work performance, math (mental performance), and typing performance (dexterity). Additionally, the "cool head, warm feet" effect, achieved through localized thermal stimulation using footwarmers at low room temperatures, was found to enhance cognitive performance, particularly in logical thinking and mental performance [75].

Productivity: Two studies [177,243] examined the physical productivity of labor workers wearing cooling vests outdoors, and six studies [85,86,92,141,186,244] investigated the effects of desk-based PV on occupant productivity. At a background temperature of 35 °C, the cooling vest tested in [177] significantly increased the workers' allowable exposure time by lowering the body's heat strain. Study [243] evaluated the cooling vest's effects on productivity with a second-order relationship between productivity loss and PMV, and it also reported improved productivity at a background temperature of 27 °C. The desk-based PV, IAQ-oriented in [85,186,244], provided non-isothermal airflow to the occupants at room temperature ranging from 23°C to 28 °C. Thermal-oriented PECS in [86,92,141] were studied in room temperatures between 14-30 °C. PECS typically employed convective cooling aimed at the occupants' upper body in the summer case, and a foot warmer in the winter case. In addition, a personalized heating system studied by Zhang et al. [86] targeted feet and forearms and revealed a higher success rate while completing math exercises. Luo et al. [92] used a similar heating system, which was found to improve self-assessed productivity. The results showed that the non-uniform environment produced by PECS did not significantly impair productivity; furthermore, productivity of some tasks was improved with the use of PECS, e.g., math (addition), Sudoku, and self-reported productivity. Overall, the effects of PECS on productivity varied depending on the tasks, with no consistent improvements observed across all measures.

Giving control to users improved occupant self-estimated productivity. Whereas, when occupants needed to concentrate, such as on a math test, occupants performed better with PECS at fixed control [53,86].

Psychological performance: A review of 10 papers on psychological aspects of PECS use covers four applications: cooling vests for protective clothing users (e.g., firemen) [52,177]; sleep-focused PECS like cooling blankets and fresh air supply [124,245]; personalized ventilation (PV) for office workers [141,156,244]; and personalized heaters for office workers [73,149,161]. Psychological effects were mainly assessed via subjective questionnaires, sometimes paired with physiological measures. Cooling vests monitored perceived exertion using the Borg scale [246] and estimated perceptual strain index using the Tikuisis equation [247]. Sleep-related PECS studied sleep quality through questionnaires and physiological measures like EEG and actigraphy. Cooling blankets improved sleep quality in hot conditions [124], while PV had no significant effect [245]. Face-directed PV improved mood and reduced fatigue better than ankle-directed PV in summer [244]. For office workers, psychological assessments included stress and motivation self-reports [141,149], PECS preferences via questionnaires or focus groups [73,161], and standardized fatigue, mood, and workload scales (Grandjean, NASA TLX) [141,244]. Psychological benefits are often correlated with improved thermal comfort [141]. Office PECS acceptance depends on thermal performance and usability factors like ergonomics and convenience [73,161], influencing psychological acceptance.

4. DISCUSSION

This discussion addresses research objectives (2) through (4) outlined in the Introduction, offering an overview of how thoroughly existing studies have examined the effects of PECS on thermal comfort, inhaled air quality, cognitive and psychological performance, productivity, and health. These impacts are discussed through the lens of both isolated benefits and integrated effects. It further uses a mobility-based classification of PECS to evaluate which types and operational conditions best support human well-being. The section concludes by highlighting current knowledge gaps, proposing directions for future research, and outlining the limitations of this review.

4.1. Unidimensional Benefits of PECS

Thermal comfort benefits: Overall, the reviewed studies indicate that using thermal PECS consistently leads to better thermal evaluation. Compared to background systems alone, PECS generally enhance thermal sensation, comfort, and acceptability. While TSV, TCV, and TAV metrics focus on individuals or an average person, other comfort metrics might be suitable for evaluating the comfort benefits of PECS in terms of a large group of building occupants, such as the thermal dissatisfaction rate or the thermal acceptability rate. Without PECS, and, according to standards ASHRAE-55 [248] and ISO 7730 [249], at least 80 % of occupants should deem thermal conditions acceptable. In contrast, the typical dissatisfaction rate in actual buildings is about 40 % [250,251]. Many studies reported improved acceptability rates surpassing 80 % and sometimes reaching 100 % when users had control over settings [50,81]. However, the effectiveness of PECS in improving thermal perception largely depended on background conditions and the type of PECS used. In environments where temperature control was already optimized, additional PECS provided only marginal benefits. Similarly, PECS seemed to be less effective at extreme temperatures, such as cooling-focused PECS at 30 °C or heating solutions below 14 °C, unless multiple devices were used in combination [252]. Building-detached systems (e.g., heated/cooled chairs, desk fans) led to the highest improvement rates, with some studies reporting whole-body comfort improvements of up to 1.8 units on the thermal sensation scale [68]. Further, these systems often showed greater effectiveness when combining multiple devices. Similarly, building semi-detached PECS, like desk-mounted PV, effectively enhanced comfort, especially in warmer conditions, with notable increases in thermal acceptability at temperatures 26-28 °C [52]. However, their impact started to decline under more extreme conditions, such as 30 °C, where acceptability drops below 65 % when user control was restricted. Building attached PECS, like ceiling fans, also generally improve perception, but the results are highly dependent on airflow rates and ambient temperatures. Some studies showed only limited improvements through ceiling fans at higher temperatures [49]. In both cases of using air movement, PV and ceiling fans, user control over these PECS significantly improved satisfaction levels. Wearable PECS had the most variable outcomes due to their limited heating and cooling capacities, but they still provided meaningful localized comfort improvements in selected studies [98,109,112]. In this review, we also examined the overall impact of PECS on specific body areas. As shown in Fig. 13, which focuses solely on PECS improving the thermal environment, they appeared to be most effective when applied to three key areas: the feet, head, and hands. For the heating case, this is in line with earlier findings, such as [253]. In the reviewed studies on cooling PECS, the neck, arms, thighs, and back were identified as the most frequently targeted body areas for local cooling. Since Fig. 13 focuses only on studies where PECS improved the thermal environment, the apparent effectiveness of specific body regions, such as the neck, arms, and thighs, may be overstated because a disproportionate number of studies specifically targeted these areas. This might lead to overlooking the effectiveness of other regions that were less frequently studied.

Benefits for indoor air quality: IAQ-focused PECS, especially PV, improve inhaled air quality by delivering clean air directly to the breathing zone, reducing exposure to contaminants from both the occupant (e.g., bio-effluents, CO_2) and the environment (e.g., office equipment). This helps increase occupant satisfaction, reduce Sick Building Syndrome (SBS), and lower the risk of infection by limiting the spread of airborne viruses. Its effectiveness depends on the background HVAC system air distribution (i.e., a stratified environment like the one established with displacement ventilation (DV) [219,218]), rather than mixing ventilation (MV), the design of the air terminal device (i.e., vertical desk grills reduce re-inhalation of exhaled air and is preferred for infection control, while round movable panels improve comfort but may disperse contaminants [254], wearable PV devices benefit from larger nozzles and optimal positioning to balance air quality and comfort [224], small outlets (e.g., 10 cm) are more prone to wake flow that draws contaminants into the breathing zone [255,256]), occupant behavior (i.e., in reality, indoor environments are not static, movement, fidgeting, and interactions disrupt airflow, reducing PV and ventilation effectiveness [212,257,258], while varied PV use affects protection levels, with low flow increasing cross-infection risk [223]). Furthermore, most PV studies focus on improving users' inhaled air quality, with limited research on background IAQ [259,223,227,211,260,261]. PV can spread exhaled contaminants in shared spaces, influenced by supply conditions, jet direction, pollution sources, and air distribution. Assistive devices like desk or chair fans and co-axial jets can be a solution but add complexity [67,69,216,262]. Many studies assume clean outdoor air with high filtration, often in areas with good air quality, ignoring polluted urban environments where outdoor pollutants (NOx, Ozone, CO, etc.) can worsen PECS performance. Future research should test PECS in real-world polluted settings and evaluate filtration methods to ensure effectiveness and comfort across diverse conditions.

Impact of PECS on human health: Health encompasses more than the absence of disease, involving physical, mental, and social well-being in interaction with the environment, yet current PECS research focuses mainly on short-term effects like thermal strain and Sick Building Syndrome (SBS) in controlled settings, with long-term health impacts largely unexplored. Most studies are short (under 4 hours), limiting insights into sustained effects, though some, like Menzies et al. [232], suggest potential year-long benefits. Furthermore, health outcomes from PECS are complex and influenced by interrelated factors; for instance,

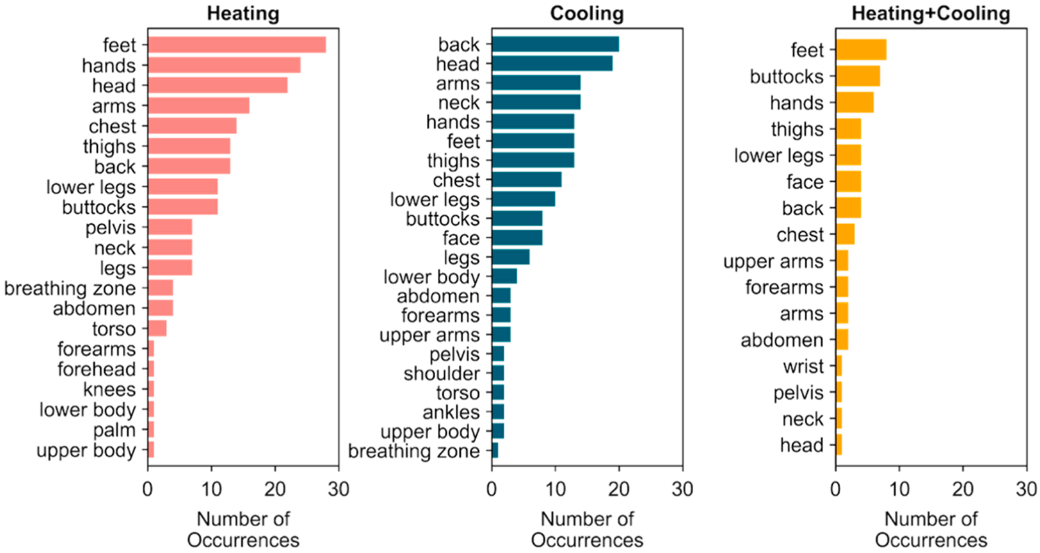


Fig. 13. Overview of local body parts reported as providing a better thermal environment.

airflow balance is key to reducing SBS without causing discomfort, and poor air quality can negate thermal comfort gains [186,226]. While PECS show consistent benefits in lowering skin temperature, sweating, and heart rate, their effectiveness on core body temperature varies based on heat stress intensity and cooling capacity. Some studies report significant core temperature reductions [97,102,106], but others show minimal or no effect [48,96,263]; this suggests that PECS with limited capacities may have limitations in fully mitigating extreme heat. Even without major physiological changes, psychological benefits of PECS, such as improved comfort and reduced distress, as in [240], are notable. Additionally, many PECS devices serve primary or complementary functions beyond IEQ, such as ergonomic support (e.g., furniture-embedded systems) or wearable comfort (e.g., wearable PECS), with consequent health implications. For instance, heated chairs, especially those with backrest heating elements, can offer therapeutic benefits in addition to thermal comfort, as shown in [163]. Overall, research on the health effects of PECS is limited due to a lack of field implementation and insufficient available data.

Human performance benefits: Overall, PECS have shown the potential to maintain or enhance cognitive performance and productivity, as measured through both objective tasks and subjective assessments. However, most PECS research has been carried out in controlled experimental environments. Only two known studies [177,243] have examined PECS effects in field conditions, specifically among outdoor labor workers. The impact of PECS on productivity is highly dependent on the surrounding environmental conditions. For instance, the use of a fan at 26 °C did not result in any measurable productivity gains. In contrast, at a higher temperature of 29 °C, performance on speed-related cognitive tasks declined, but the use of a fan helped to offset this decline partially [81]. Moreover, the influence of PECS on productivity varied across different types of cognitive tests, with no consistent improvements observed. This variability is likely because different tests engage distinct cognitive functions. Interestingly, in some studies, participants who had control over their PECS reported improved subjective performance even as their objective performance declined, such as in tasks involving math [53,86]. A possible explanation is that the need to adjust or interact with the PECS manually may be a cognitive distraction, reducing concentration and task performance. From a psychological perspective, improving thermal comfort through PECS can positively influence mood and well-being. Currently, the body of research on how PECS affect human performance remains limited. There is a clear need for the development of standardized procedures to systematically evaluate work performance in the context of PECS use.

4.2. *Integrated Effects of PECS*

Combined effects of thermal and IAQ-focused PECS on comfort, health, and human performance: The integration of thermal and IAQ-focused PECS has demonstrated potential to enhance the microenvironment around the person by addressing temperature regulation and air quality simultaneously. Studies have shown that PV can enhance the cooling effect of localized airflow, reduce thermal discomfort, and lower the required cooling intensity of thermal PECS [30,39]. Similarly, local air purification systems can improve perceived air quality, further enhancing overall comfort levels even in thermally optimized environments [32]. A key finding in recent literature is that combining PECS for temperature control and IAQ can create a cumulative improvement in user satisfaction. For example, heating PECS can be complemented by humidification or filtered air distribution, reducing the perception of dry air discomfort and improving respiratory comfort [35,39]. Some studies on the integration of thermal and IAQ-focused PECS have investigated health and performance outcomes, going beyond comfort responses. Most studies examining the health effects of these devices have focused on SBS symptoms, such as eye irritation, headaches, and fatigue, rather than heat stress, which has been primarily analyzed in relation to wearable heating and cooling devices (i.e., thermal-only PECS). Most studies on SBS symptoms have investigated the effect of combined thermal and IAQ devices compared to thermal-only and IAQ-only systems and have yielded mixed but promising results in mitigating SBS symptoms. However, their effectiveness depends on factors such as temperature, air speed, cleanliness of the distributed air, and overall environmental conditions. Specifically, PV delivering clean, drier, and cooler air with balanced airflow has been found to provide the most positive health outcomes [133,226]. Conversely, facial ventilation in warm conditions or exposure to warm, high-speed, and recirculated polluted air can worsen eye dryness, respiratory irritation, and overall discomfort, potentially negating the benefits of these systems in terms of comfort [51,85,133,187,189]. From a performance perspective, research on the impact of combined thermal + IAQ PECS remains limited. While most studies investigating occupant performance have focused on thermal PECS, such as foot warmers, desk fans, and wearable devices, only one study, Melikov et al. [52], has specifically investigated the performance effects of a combined thermal + IAQ PECS. The findings suggest that integrating thermal and IAQ control positively influences cognitive function, particularly in terms of concentration and overall work performance.

Multi-sensory effects of PECS: Only a handful of studies, such as those by Al Assaad et al. [264], Zhao et al. [265], and Tan et al. [72], have explicitly examined the multi-sensory effects of PECS when used in combination or isolation (i.e., thermal-only or IAQ-only). Existing studies tend to evaluate single effects (e.g., comfort only), overlooking the potential synergies or trade-offs on more than one response that may arise when PECS are deployed. However, understanding multi-sensory responses is critical, as indoor environmental conditions are inherently interconnected, with multiple parameters influencing various human responses simultaneously [266,267]. The effects of PECS could be one-directional, where improvements in one domain, such as enhanced thermal comfort, lead to better health outcomes and increased productivity. For instance, a device that optimizes local thermal conditions might reduce discomfort and cognitive strain, allowing occupants to focus better and maintain efficiency over extended periods. However, these effects could also be conflicting. A device that improves thermal comfort may unintentionally compromise health or productivity, depending on its design and operating parameters. For example, convection-based devices that direct airflow toward an occupant's face may help regulate perceived temperature, enhancing comfort in warm environments. However, prolonged exposure to air movement near the face can lead to eye dryness and irritation, potentially increasing SBS symptoms such as eye discomfort, headaches, and concentration difficulties. Similarly, PV that recirculates indoor air instead of supplying fresh, filtered air might inadvertently increase exposure to indoor pollutants, affecting respiratory health while still providing localized thermal relief. These examples highlight the need to study the combined influence of multiple environmental parameters affected by PECS, such as air flow, temperature, humidity, and air quality, on a range of human responses, including comfort, performance, and health. A holistic approach is needed to determine whether these systems truly optimize the indoor environment without unintended negative consequences.

4.3. Knowledge gaps and future research directions

The domain of PECS is still in the nascent development phase, and more so in practice. However, it holds immense importance in the contemporary and future world due to its promises of providing better IEQ, comfort, human productivity, and health benefits. This paper reviews the current body of literature on PECS from multiple perspectives. However, as an emerging field, it has yet to address several critical areas, which are outlined below:

- The method and guidelines to design, integrate, and control PECS for optimum human benefits need to be developed: For thermal PECS, research needs to enhance design and heating/cooling capacity to perform effectively across various conditions, including heat stress, by accounting for different heat transfer modes and ensuring proper integration with background HVAC systems. For IAQ-focused PECS, especially personalized ventilation (PV), design improvements should enhance air delivery and comfort while accounting for real-world factors like occupant movement, airflow direction, and cross-contamination in shared spaces.
- Standardized procedures to systematically evaluate human performance in the context of PECS use need to be developed: Further research is needed to better understand the impact of PECS on human performance, for instance, to objectively measured work productivity under realistic work tasks, extended exposure durations, and with optimized control strategies, as the current literature on this topic remains limited.
- Better understanding inter-individual variability in human responses to PECS: Most of the reviewed studies focused predominantly on participants in their 20's-30′s, with only two studies [50,90] categorizing participants by age groups and comparing their subjective responses. Since a core aim of PECS is to accommodate individual differences, it is essential to evaluate how effectively these systems address variability across diverse users.
- Better understanding of the combined use of different PECS: Exploring the combined use of thermal and IAQ-focused PECS is essential, as their interaction can impact occupant comfort, health, and performance. Poor coordination, such as PV airflow disrupting localized heating or cooling, may create uneven microclimates. Simultaneous operation can also cause conflicting controls; further research is needed to optimize their balance, considering user adaptability.
- Investigation of multi-sensory effects: The influence of PECS beyond comfort and perception and the potential trade-offs should be investigated not only for PECS used in combination but also for PECS used in isolation.
- Study of multi-domain effects: Due to the lack of studies on the topic, future research should investigate the multi-domain effect of PECS, more specifically their cross-effect, to understand broader implications. For instance, future studies should investigate how a PV system affects not only thermal comfort and air quality (i.e., same-domain effect) but also acoustics (i.e., cross-domain effect).

4.4. Limitations of the review

This work provides a systematic analysis of literature up to mid-2023, offering a foundation for understanding recent trends in PECS research. Future studies published from 2024 onward are expected to expand on these findings and help address the identified gaps. In addition, this review presents a qualitative synthesis, with a detailed meta-analysis for a subset of the papers screened in this review, currently in progress as part of IEA EBC Annex 87. The upcoming publication will establish a more quantitative link between PECS performance, their technical features, and associated human benefits.

5. Conclusions

This systematic review highlights the extensive progress made over the past 25 years (up to mid-2023) in the field of Personalized Environmental Control Systems (PECS) and their potential benefits for enhancing thermal comfort, indoor air quality (IAQ), health, and human productivity. It explores existing studies on human-centered PECS, evaluates how previous research has addressed comfort and well-being, identifies the types of PECS that offer human-related benefits, and highlights key knowledge gaps to inform future research in personalized environmental quality. While previous reviews on PECS have predominantly focused on a single environmental domain, this review emphasizes the importance of addressing the effect of both thermal and IAQ domains, which are often interrelated. Findings suggest that PECS, particularly building detached ones, can often improve thermal sensation, comfort, and acceptability; a frequent combination of various PECS also leads to better ratings. Enhanced IAQ through personalized ventilation systems has also demonstrated potential for improving air quality in the breathing zone, thereby reducing exposure to contaminants. However, the variability in study designs, subjective scales, performance metrics, and the lack of consistent evaluation frameworks across different PECS types highlight the need for more standardized research methodologies. Moreover, as just a few studies in our review only reported short-term improvements (i.e., within a day) in health and productivity associated with PECS, there is a clear lack of research exploring their long-term health impacts (i.e., effects observed over periods of several months or more) and applicability across diverse built environments. Future research should work toward building a more comprehensive framework for evaluating how PECS affect human performance, considering both thermal comfort and indoor air quality (IAQ) under realistic, long-term conditions. It is also important to expand studies into multi-sensory environments, such as visual and acoustic factors, and explore the interactions between these domains. Developing standardized metrics for human performance will be crucial for linking PECS use to measurable outcomes. Furthermore, understanding the connections between thermal comfort, IAQ, health, and human performance is key to creating holistic, human-centered PECS solutions that truly enhance well-being. As the PECS field continues to evolve, future work should also incorporate and build upon studies published from 2024 onward.

CRediT authorship contribution statement

Dolaana Khovalyg: Writing – original draft, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mariya P. Bivolarova:** Writing – original draft, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Jun Shinoda:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Douaa Al-Assaad:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marika Vellei:** Writing – original draft, Visualization, Software, Investigation, Formal analysis. **Karol Bandurski:** Writing – original draft, Investigation, Formal analysis. **Giorgia Chinazzo:** Writing – original draft, Investigation, Formal analysis. **Ongun B. Kazanci:** Writing – original draft, Investigation, Formal analysis, Conceptualization. **Joyce Kim:** Writing – original draft, Investigation, Formal analysis. **Tobias Kramer:** Writing – original draft, Investigation, Formal analysis, Data curation. **Aleksandra Lipczynska:** Writing – original draft, Investigation, Formal analysis. **Shichao Liu:** Writing – original draft, Investigation, Formal analysis. **Wilmer Pasut:** Writing – original draft, Investigation, Formal analysis. **Rajan Rawal:** Writing – original draft, Resources, Investigation, Formal analysis. **Chandra Sekhar:** Writing – original draft, Investigation, Formal analysis. **Ruiji Sun:** Writing – original draft, Investigation, Formal analysis. **Zhibin Wu:** Writing – original draft, Investigation, Formal analysis. **Alireza Afshari:** Writing – review & editing, Investigation. **Pablo Martinez-Alcaraz:** Writing – review & editing, Investigation. **Maíra André:** Writing – review & editing, Investigation. **Touraj Ashrafian:** Writing – review & editing, Investigation. **Pedro de la Barra:** Writing – review & editing, Investigation. **Mateus Bavaresco:** Writing – review & editing, Investigation. **Katharina Boudier:** Writing – review & editing, Investigation. **Chungyoon Chun:** Writing – review & editing, Investigation. **Joon-Ho Choi:** Writing – review & editing, Investigation. **Adrian Chong:** Writing – review & editing, Investigation. **Sarah Crosby:** Writing – review & editing, Investigation. **Renata De Vecchi:** Writing – review & editing, Investigation. **Ricardo Forgiarini Rupp:** Writing – review & editing, Investigation. **Matteo Favero:** Writing – review & editing, Investigation. **Natalia Giraldo Vasquez:** Investigation. **Matheus Geraldi:** Investigation. **Veronica Martins Gnecco:** Investigation. **Akshit Gupta:** Investigation. **Sabine Hoffmann:** Investigation. **Wooyoung Jung:** Writing – review & editing, Investigation. **Meng Kong:** Writing – review & editing, Investigation. **Minyoung Kwon:** Investigation. **Giulia Lamberti:** Investigation. **Yoonhee Lee:** Investigation. **Alessandra Luna-Navarro:** Writing – review & editing, Investigation. **Fatemeh Nabilou:** Writing – review & editing, Investigation. **Larissa Pereira de Souza:** Investigation. **Ilaria Pigliautile:** Writing – review & editing, Investigation. **Anna Laura Pisello:** Writing – review & editing, Investigation. **Kai Rewitz:** Writing – review & editing, Investigation. **Roberto Rugani:** Writing – review & editing, Investigation. **Sasan Sadrizadeh:** Writing – review & editing, Investigation. **Peter Simmonds:** Investigation. **Andrew Sonta:** Investigation. **Marc Syndicus:** Writing – review & editing, Investigation. **Fatih Topak:** Writing – review & editing, Investigation. **Giulia Torriani:** Investigation. **Luca Zaniboni:** Investigation.

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.

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APPENDIX A: Overview of studies included in the systematic review

Table 1
References to studies considered in the systematic review.

PECS focus domain	Classification of papers per human involvement			
	Humans	Manikin	Human model	No subject
Thermal	[17,18,31,48–177]	[48,200,264,268–301]	[302–325]	[326–347]
Thermal+IAQ	[178–199]	[348,219,349,350,259,220,222,225,254,212,211,265,351,213,352,353,354,355,214,356]	[215,357,257,209,207,358–360,208,361–363]	[364–367]
IAQ	[368,226,227,233,232,244,245,260,369,370]	[371,216,204,221,218,255,210,223,224,205,372,373,374,375,376,377,378]	[379,206,380,217,381]	[256,382–384]

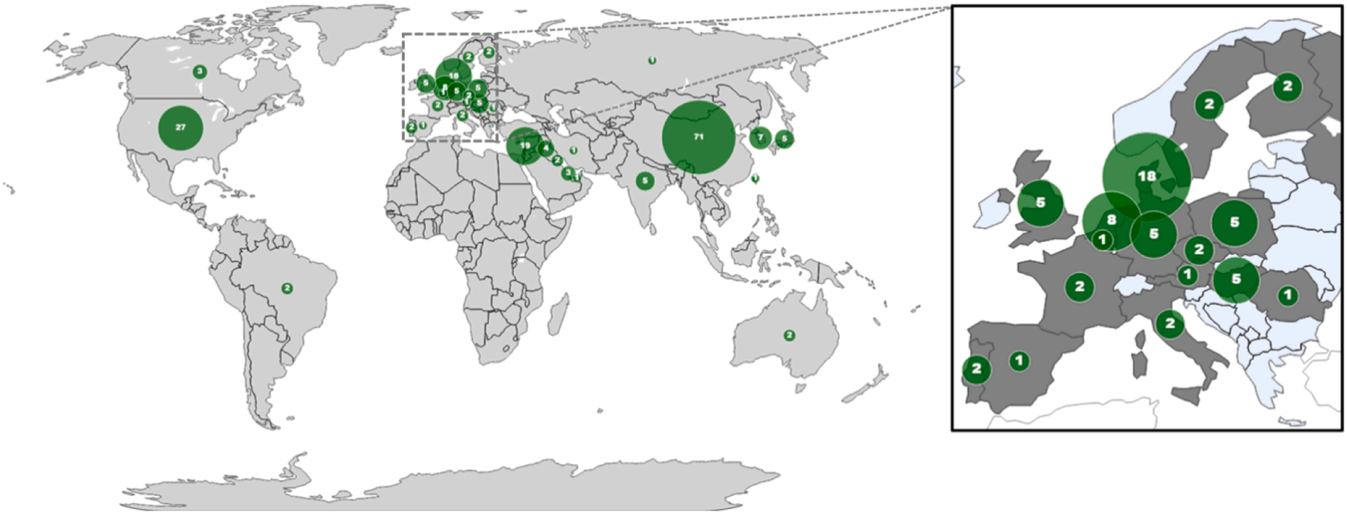

Fig. 14. Geographical distribution of the studies considered in the systematic review (the number indicates the number of original research publications).

Table 2
References to PECS studies (with humans) according to their effect on thermal comfort.

PECS mobility types	Categories of the effect of PECS compared to no PECS conditions (reference)				
	Better	Circumstantial	Same	Worse	No comparison
Building attached	Thermal [18,49,50], Thermal+IAQ [199]	-	-	-	Thermal [147], Thermal+IAQ [55,193]
Building semi-detached	Thermal [51–59], Thermal+IAQ [178–186]	Thermal+IAQ [192]	Thermal [135]	-	Thermal [148–156], Thermal+IAQ [194,195]
Building detached	Thermal [31,60–95], Thermal+IAQ [187–191]	Thermal [133]	Thermal [17,73, 136–141]	Thermal [144–146]	Thermal [157–166] Thermal+IAQ [196]
Wearable devices	Thermal [48,79,96–122]	Thermal [134]	Thermal [142,143]	-	Thermal [158–161,168–172]
Others	Thermal [123–132]	-	-	-	Thermal [173–176], Thermal+IAQ [197,198]

Table 3
References to PECS studies according to their effect on indoor air quality.

PECS mobility types	Categories of the effect of PECS compared to no PECS conditions (reference)				
	Better	Circumstantial	Same	Worse	No comparison
Building attached	IAQ [216,217], Thermal+IAQ [209]	-	-	-	IAQ [385,256,261], Thermal+IAQ [193,348,199, 257,355]
Building semi-detached	IAQ [204,218,210,226,233,260,205,373,375,377, 380–382], Thermal+IAQ [179,181–186,190,191, 195,357,349,259,225,207,254,211,265,353,208, 361]	IAQ [376], Thermal+IAQ [254]	Thermal+IAQ [364]	-	IAQ [369,260,223,221,368,374,383,244,370,346, 232], Thermal+IAQ [351,178,359,352,360,365, 180,257,356,194,366,219,222,195,367,362]
Building detached	Thermal+IAQ [212–215]	-	Thermal+IAQ [363]	-	IAQ [372,255,384,245,227], Thermal+IAQ [187, 188,181,196,220]
Wearable devices	IAQ [371,224], Thermal+IAQ [191]	-	-	-	-
Others	IAQ [206, Thermal+IAQ [256,354,198]	-	-	-	IAQ [379], Thermal+IAQ [197,350]

Table 4
References to PECS studies according to their effect on human health.

Domain	Categories of the effect of PECS compared to no PECS conditions (reference)			
	Better	Circumstantial	Same	Worse
Studies concerning SBS symptoms:				
Thermal	[98]	[51]	-	[85]
Thermal+IAQ	[81,181,190]	[186,189]	-	[187,189]
IAQ	[[232]	[226]	-	-
Studies concerning physiological state:				
Thermal	[48,62,70,73,79,97,103,106,107,112,115,120,121,124,132,[134,140,161,171]	[68,72,98,99,102,158]	[50,64,94,96,143]	-
Thermal+IAQ	[190]	-	-	-
IAQ	-	[245]	-	-

APPENDIX B: Overview of voting scales used in thermal PECS studies

An overview of the most commonly used metrics for subjective assessment of thermal PECS, in relation to the background air temperatures of the studies, focusing exclusively on PECS that delivered “better” thermal conditions, is presented hereafter.

Thermal Sensation Votes (TSV): The TSV is the primary subjective measure used to evaluate whole-body thermal sensation in the reviewed studies. Notably, 77 % of these studies employ TSV as a key indicator of PECS performance. Regarding the scales used, as shown in Fig. 15(a), the ASHRAE 7-point scale (-3: “cold,” -2: “cool,” -1: “slightly cool,” 0: “neutral,” +1: “slightly warm,” +2: “warm,” +3: “hot”) is the most commonly applied (e.g., in [63,73,109]), appearing in 52 % of studies (e.g., in [65,84,110]) assessing whole-body thermal sensation. Meanwhile, approximately 19 % of studies (e.g., [68,86,159]) adopt the 9-point scale introduced initially by Zhang et al. [86]. Less frequently used alternatives include the 5-point scale (e.g., in [125,163]), asymmetric 7-point scale (in [79,130]), and 10-point scale (in [120]) or 13-point scale (in [177]). A significant portion of the reviewed studies, 45 %, assess local thermal sensation by focusing on specific body parts. Among these, the use of scale varies slightly: the 7-point scale again is dominant, applied in 68 % of the studies (e.g., in [73,74,85]), while the 9-point scale is used in the remaining 32 % (e.g., in [65,68,83]). The top five local body parts most frequently studied are feet, hands, head, back, and arms, as illustrated in Fig. 16. Notably, for feet and hands, being among the most sensitive and influential on overall comfort in cool-cold conditions [386,387,203], the more granular 9-point scale is used in most cases (e.g., in [68,83,103,127]), reflecting a focus on capturing the nuanced thermal sensation of these highly sensitive areas.

Thermal Comfort Votes (TCV): While the most used subjective index for evaluating thermal comfort is TSV, it might not be able to demonstrate the benefit of PECS, especially in air-conditioned buildings, where the TSV of the background environment is usually within +1 (slightly warm) and -1 (slightly cool). After having the PECS, the thermal sensation vote could be close to 0 (neutral) or still close to -1 (slightly cool); thus, the difference before and after having the PECS is usually insignificant. The local-body TSV has the same issues as the whole-body. For example, a field study by Bauman et al. [388] was conducted at the ambient air temperature ranges between 20 °C and 27 °C throughout the year. In the summer season, the average TSV is close to +1 (slightly warm) before having PECS and is close to 0 (neutral) after having PECS. In the winter season, the average TSV is -1 (slightly cool) without PECS and is still -1 (slightly cool) after having PECS. Thermal Comfort Vote (TCV) is a more direct, thus appropriate metric for evaluating the comfort benefit of PECS. Fig. 15(b) provides an overview of thermal comfort vote (TCV) scales used in the PECS investigations, and it illustrates that only 28 % of studies adopt the TCV metric. The 7-point and 6-point scales are the most used ones, appearing in 11 % of studies (e.g., in [60,86,158,161]). The 7-point scale has an explicit 0 (neutral) point, while the 6-point scale lacks the central “neutral” category. The 4-point scale is also commonly used, appearing in 7 % of studies (e.g., in [59,74,160]), which ranges from -2 (very uncomfortable) to 2 (very comfortable).

Thermal Acceptability Votes (TAV): Approximately 30 % of the studies investigating PECS evaluated thermal acceptability, employing a variety of scales (Fig. 15(c)). These include 2-point, 3-point, 4-point, 6-point, 7-point, and 9-point scales, and results based on thermal sensation and comfort rates, such as votes for “*cold but comfortable*” or “*warm but comfortable.*” Among the studies reporting thermal acceptability, the great majority (65 %) used a 4-point scale (e.g., in [52,53,55,203]), followed by 10 % using a 7-point scale (e.g., in [137,158,159]), 8 % each a 9-point scale (e.g., in [68,71]) and a 6-point scale (e.g., in [50,67,69,76]), 5 % a 2-point scale (e.g., in [62,87,138]), and about 1.5 % each employing a 3-point scale (e.g., in [115, 152,180]), 5-point scale (e.g., in [60]) or deduce the response from thermal sensation and comfort responses (e.g., in [389]). Fig. 15(c) illustrates that the use of different response scales is generally evenly distributed across the investigated background air temperature range. However, notable exceptions include the 9-point scale, which is more frequently employed in out-of-comfort conditions (i.e., at 18 °C and 30 °C), and the 2-point scale, which is absent within the comfort range (20–25 °C). The most frequently used scale, the 4-point scale, typically ranges from “clearly unacceptable” (−1) to “clearly acceptable” (+1) and is sometimes presented as either a continuous or discrete scale. The design and presentation of the scale often compel subjects to clearly distinguish between acceptable and unacceptable conditions, dividing the acceptability scale into two distinct parts: one ranging from “*clearly unacceptable*” to “*just unacceptable,*” and the other from “*just acceptable*” to “*clearly acceptable.*” Sometimes studies associate "*just acceptable*" and "*just unacceptable*" with a value of 0, but most often with a value of +/−0.1. Rarely used scales include the 3-point acceptability scale (+1, 0, -1) (e.g., in [152]) and a 5-point scale (e.g., in [60]) categorizing acceptability into “*acceptable,*” “*barely acceptable,*” “*neutral,*” “*barely unacceptable*”, and “*unacceptable.*” While most studies focused on whole-body thermal acceptability, a few evaluated acceptability for individual body parts, including the head, chest, back, and extremities (e.g., in [72,85,133,322,323]).

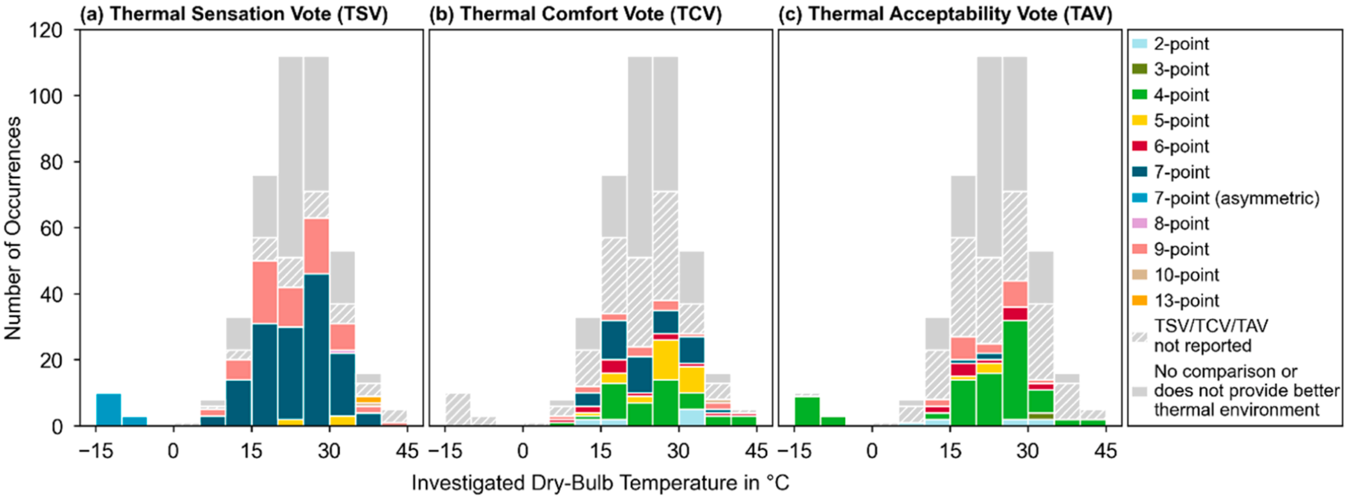

Fig. 15. Overview of scales used in the analyzed studies: (a) Thermal Sensation Vote (TSV), (b) Thermal Comfort Vote (TCV), (c) Thermal Acceptability Vote (TAV).

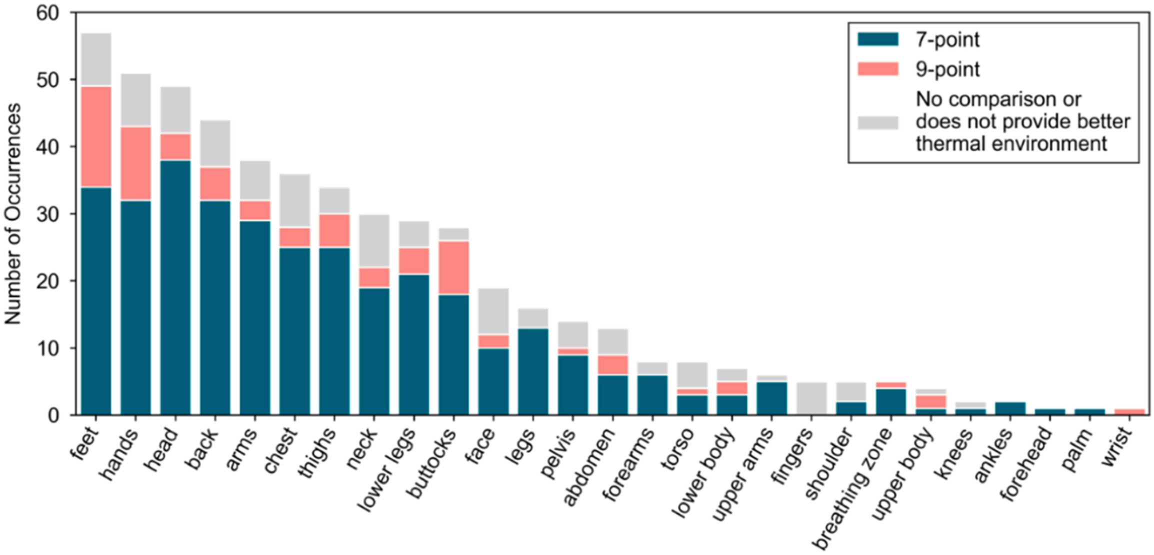

Fig. 16. Overview of local body parts analyzed and the TSV scales used in the respective studies: The analysis highlights a strong focus on the extremities, particularly the feet and hands, as they are the most sensitive to changes in the thermal environment.

Data availability

Data will be made available on request.

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