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# Human cooling solutions: alternatives to conventional cooling solutions

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To break the cycle of traditional air conditioning, rising carbon emissions, and increasing urban heat, a fundamental redesign of how humans achieve thermal comfort is essential. This review explores emerging technological trends in alternative cooling solutions from two perspectives. First, localized or personal cooling devices are gaining attention as a sustainable alternative to conventional space cooling. However, current technologies remain insufficient to fully replace traditional air conditioning. This review examines the limitations of commercial personal cooling devices and highlights advancements aiming to bridge this gap. Second, given the improbability of personal cooling entirely replacing space cooling in the near future, alternative large-scale cooling approaches must also be considered. This review discusses current and emerging cooling cycles, along with complementary technologies designed to enhance energy efficiency, including district cooling, radiative cooling, cooling paints, and the integration of green spaces.

## KEYWORDS

active cooling technologies, cooling solutions, human cooling, localized cooling, passive cooling technologies, personal cooling wearables, sustainable cooling, sustainable space cooling

## 1 Introduction

Climate scientists widely agree that even with dramatic action to lower carbon emissions, dangerous levels of heat and humidity are likely to become more common ([The New York Times, 2022](#)). Over-reliance on air-conditioning ([Muruganat, 2020](#)) contributes significantly to carbon emission and the Urban Heat Index (UHI) ([Robin, 2018](#)), which inevitably contributed to the rising temperature. It is estimated that traditional cooling and refrigeration make up to 10% of global greenhouse gas (GHG) emissions, with an increasing trend, set to double by 2050 ([Dong et al., 2021](#)). Therefore, there is an urgent need to redesign the way humans achieve thermal comfort to break out of this vicious cycle, while at the same time offering a solution for the rising heat levels.

In recent years, extensive research has been conducted to address this challenge. A search on “Human Cooling Technology” on different databases (Web of Science, Science Direct, and SpringerLink) reveals an exponential increase in publications and citations on the topic of human cooling technology, as shown in [Figure 1](#). This trend reflects the growing demand for alternative human cooling solutions. These emerging technologies, which differ from traditional cooling and refrigeration methods, can be broadly categorized into two groups: localized/personal cooling devices and alternative space cooling technologies. It is

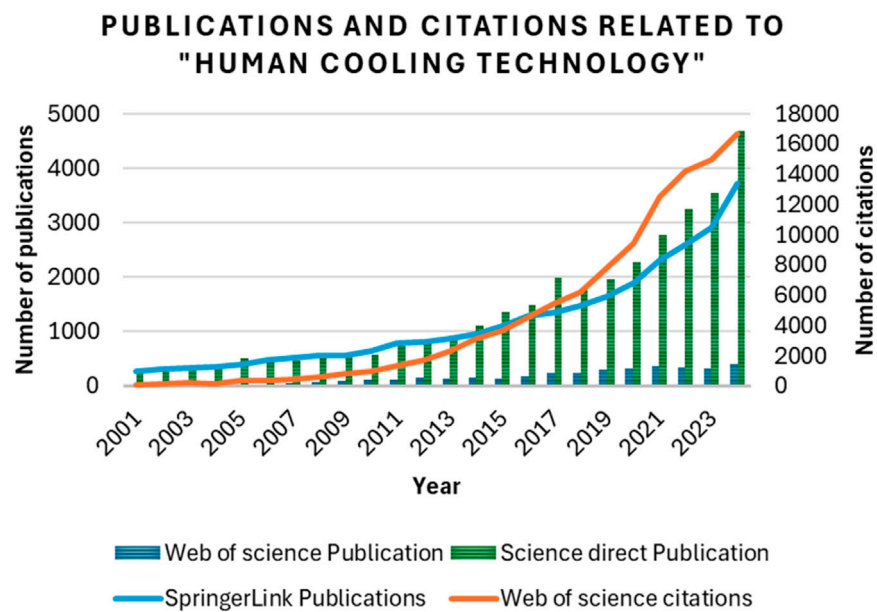


FIGURE 1  
Number of publications and citations relating to the topic of human cooling technology from 2001 to 2024.

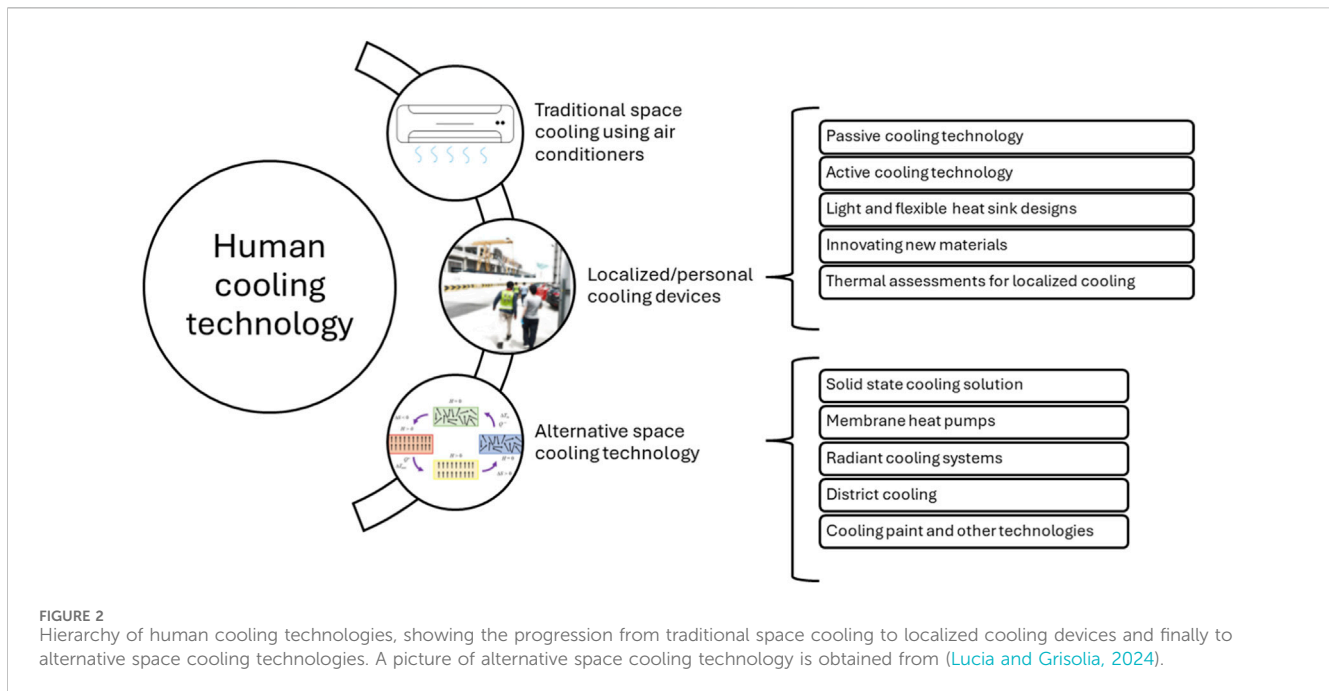
envisaged that technological advancements in both categories are essential to move towards sustainable human cooling.

Personal cooling devices (PCD) use passive, active, or hybrid cooling technology (Rahimi et al., 2024), to provide localized cooling. They are seen as a sustainable alternative to traditional space cooling due to two main factors. First, traditional cooling technologies are currently based on cooling of large indoor spaces, which can lead to up to 70% energy wastage (Xu et al., 2022). PCD has the potential to provide thermal comfort without the need to cool down large indoor spaces, reducing significant wastage in energy. Second, personal cooling devices have the potential to provide sufficient thermal comfort in situations that can be challenging for traditional air conditioners (Kishore et al., 2019). Achieving thermal comfort in such situations, such as outdoors, is also critical to prevent prolonged exposure to high temperatures in many areas, such as occupational safety, sports performance, and even medical applications. However, while there already exist commercial personal cooling devices, the technology is still not ready to provide sufficient thermal comfort to replace conventional space cooling. This review summarizes the limitations of current commercial personal cooling devices and highlights the current state-of-the-art technology that aims to narrow this gap.

In the realm of space cooling, alternative cooling approaches to replace or improve the energy efficiency of conventional cooling systems are an active area of research. Vapor-compression (VC) air-conditioning systems are widely used but are energy-intensive and rely on non-environmentally friendly refrigerants (Abedrabboh et al., 2022). Alternative cooling solutions that can reduce the energy consumption of large space cooling are much desired. However, to date, the efficiency of VC systems is still hard to surpass, and VC cycles with eco-friendly refrigerants are still the go-to solution in the near future (El Fil et al., 2021; Abedrabboh et al., 2022). Sustainable space cooling solutions, such as solid-state

cooling technologies, hold great promise as alternatives to VC systems; however, they must further improve their efficiency and overcome existing technical challenges, as most remain at early stages of technological development and demonstration (Elnagar et al., 2023). In this review, apart from reviewing the different cooling cycles, other technologies that aim to increase the energy efficiency of space cooling systems are included. This includes district cooling solutions, radiative cooling systems, and cooling paint technology.

This review provides a comprehensive analysis of emerging cooling technologies, as summarized in Figure 2. Section 2 focuses on personal cooling devices (PCD), reviewing existing commercial products and current developments in passive and active cooling technologies. Given the novelty of localized cooling, the section concludes with an overview of thermal assessment methods crucial for its adoption. Section 3 examines space cooling technologies, covering traditional vapor-compression (VC) cycles, alternative solid-state cooling methods (e.g., magnetocaloric, electrocaloric, and elastocaloric cooling), and emerging solutions like membrane heat pumps and radiant cooling. Additionally, complementary technologies—such as district cooling and cooling paints—are discussed for their potential to enhance energy efficiency. By reviewing these advancements, this paper highlights promising alternatives for improving human thermal comfort. While several recent reviews have examined either personal cooling devices (Rahimi et al., 2024; Shou and Li, 2025; Wang et al., 2026) or alternative space cooling technologies (Abedrabboh et al., 2022; Elnagar et al., 2023). However, these streams are typically treated in isolation. This review integrates both perspectives into, explicitly comparing localized and space-based approaches. Furthermore, while prior reviews have assessed technical performance, comparatively less attention has been given to user-centered limitations, practical



deployability, and the implications for standards and policy. To address these gaps, this study aims to (i) systematically review and compare emerging personal and space cooling technologies within a unified “human cooling” framework, (ii) critically assess their technological limitations and real-world feasibility using both literature synthesis and user survey insights, and (iii) identify design, operational, and policy-relevant implications for the development of sustainable cooling strategies. By doing so, this work seeks to provide a coherent foundation for both future research and practical implementation of next-generation cooling solutions.

## 2 Personal cooling devices (PCDs)

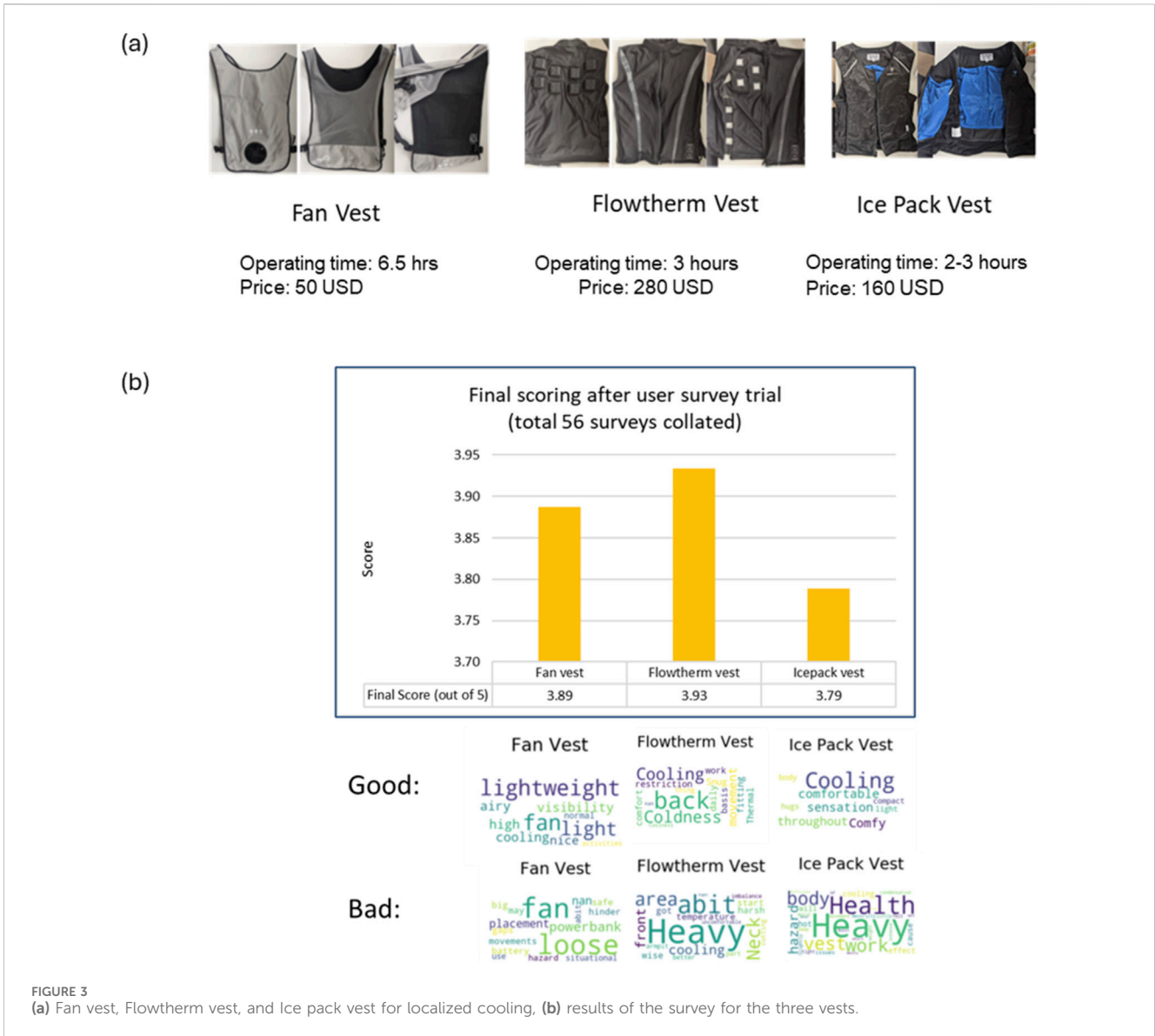
Among various cooling strategies, personal cooling devices (PCDs) and garments, which cool the skin directly through wearable systems, are gaining attention for their portability and accessibility (Feng et al., 2024; Yi et al., 2017). However, despite the availability of personalized cooling wearables, widespread adoption remains limited due to challenges such as weight, ergonomics, durability, power consumption, and inadequate temperature control. The research team conducted a medium-scale market and user survey (IRB Application 2021017) to validate this observation. Three commercially available cooling products—a fan-based vest, a flow thermoelectric (Flowtherm) vest, and an ice-packed vest—were evaluated, as shown in Figure 3a. These products differ significantly in their cooling mechanisms, operating durations, and costs (see Supplementary Material, Section 1, for detailed specifications).

In total, 56 participants evaluated the products, and the Flowtherm thermoelectric (TE) vest received the highest overall satisfaction rating (average score: 3.93 out of 5) as shown in Figure 3b. The TE-based vest operates using the Peltier effect, enabling lightweight, solid-state, and tunable cooling performance

(Kishore et al., 2019; Hong et al., 2020). In contrast, the ice-packed vest was frequently described as heavy and uncomfortable due to condensation buildup, while the fan-based vest offered only limited cooling and raised safety concerns related to the exposed fan blades. Despite the advantages of the Flowtherm vest, it faces other challenges such as limited battery life (approximately 3 h), high production costs, and increased device weight. These limitations restrict their practicality for users—particularly outdoor or industrial workers—who require continuous, long-duration cooling solutions throughout the workday.

Consistent with prior evaluations of wearable cooling technologies (Kishore et al., 2019; Feng et al., 2024), our survey confirms that current commercial PCDs remain inadequate as stand-alone replacements for space cooling due to limitations in duration, ergonomics, and cooling capacity. However, in contrast to earlier reviews that emphasized single-technology solutions, our synthesis highlights hybrid systems (e.g., thermoelectric–fan, PCM–air) as offering the most promising balance between cooling effectiveness and energy efficiency. To promote energy savings and individualized thermal comfort, developing personalized thermoregulation technologies is crucial. This involves the intricate balancing of the macro-environmental temperatures and the micro-environmental conditions between the body and clothing (Wei et al., 2023).

The user survey provides indicative insights into the usability and perceived performance of selected personal cooling devices, but several limitations should be noted. The sample size and participant pool may not fully represent diverse user groups, occupational contexts, or climatic conditions, and responses may be influenced by short trial durations and prior user expectations. Moreover, only a limited set of commercial products was evaluated under controlled conditions, which does not capture long-term use or extreme environments. Consequently, while the survey highlights important trends, the findings should not be overgeneralized, and



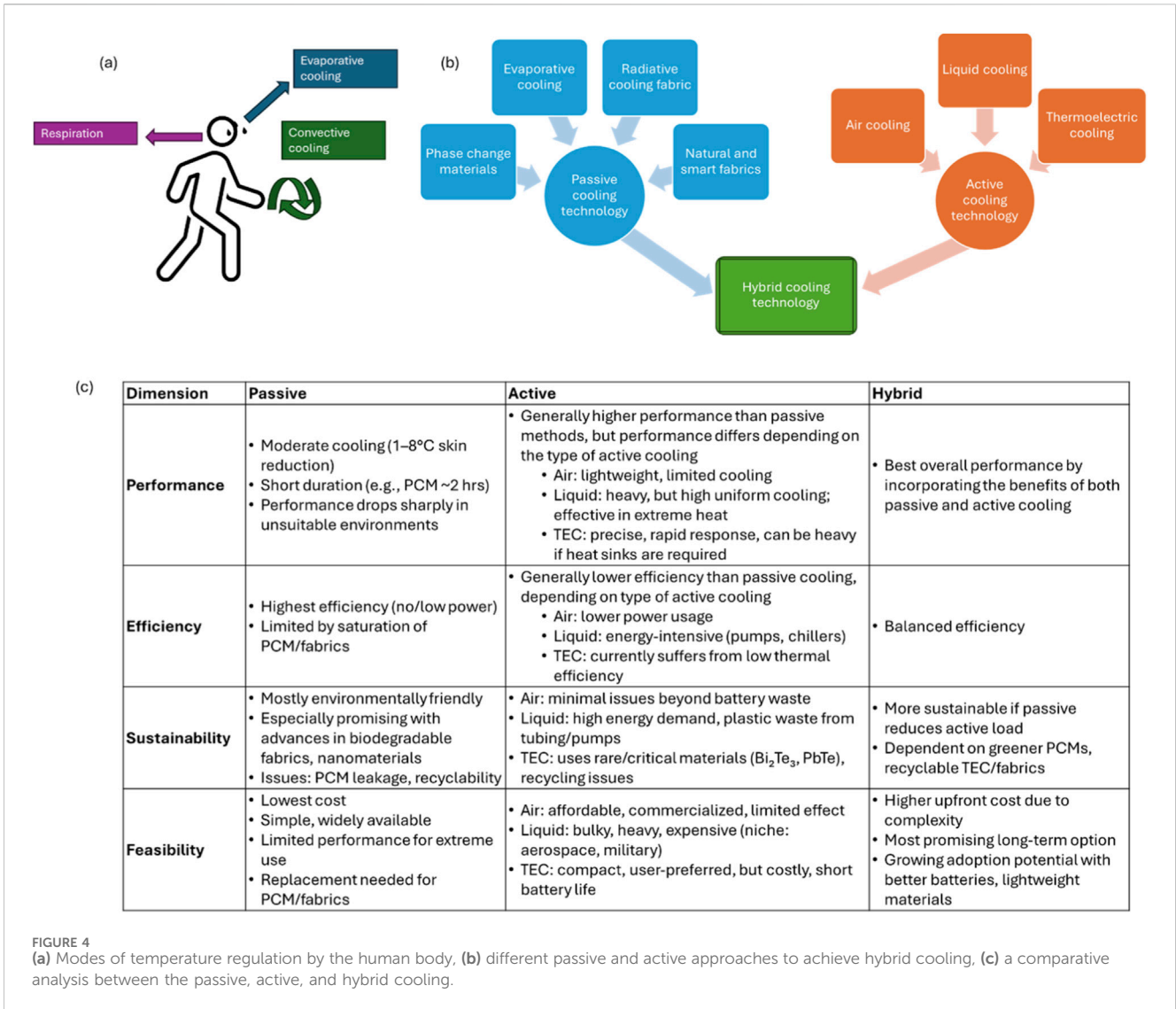
broader field studies with larger and more diverse populations are needed to strengthen external validity.

The human body naturally regulates its temperature through three primary mechanisms, convection, radiation, and perspiration, as illustrated in Figure 4a. These physiological cooling pathways help maintain thermal comfort under normal environmental conditions. However, under extremely high ambient temperatures or in harsh occupational environments (e.g., foundries, construction sites, or agricultural fields), these natural processes become insufficient to dissipate the accumulated metabolic heat. To address this limitation, hybrid cooling technologies have emerged as an effective strategy. These systems combine both passive and active cooling approaches to provide localized and enhanced personal cooling, as shown in Figure 4b. In such systems, passive cooling techniques (e.g., radiative cooling, evaporative materials, or thermal insulation layers) are integrated with active components (e.g., thermoelectric coolers, micro-fans, or liquid circulation units) to optimize thermal comfort while minimizing energy consumption (Wei et al.,

2023). A comparative overview of these cooling strategies—passive, active, and hybrid—is presented in Figure 4c, evaluating their performance, energy efficiency, sustainability, and practical feasibility. This comparison highlights that hybrid systems often offer the best trade-off between cooling effectiveness and operational sustainability, particularly for wearable or localized cooling applications.

## 2.1 Passive cooling technology for personal cooling devices

Cooling fabrics improve comfort by optimizing the body's thermoregulatory processes, including radiation, convection, evaporation, and respiration. The choice of fiber materials, nanomaterials, polymers, phase change materials (PCM), functional coatings, and shape memory alloys enhances the cooling effect (Xue et al., 2024). This section expands on four



main passive cooling technologies: (i) Phase Change Materials (PCM), (ii) Evaporative Cooling, (iii) Radiative Cooling, and (iv) Natural and Smart Fabrics.

### 2.1.1 Phase change materials (PCM) in clothing

Phase Change Materials (PCM) absorb heat from the human body, ensuring thermal comfort for the wearer. As PCM undergoes a phase transition from solid to liquid, it absorbs excess heat through conduction from the body. Common PCMs include paraffin waxes, hydrated salts, and fatty acids, often embedded in textiles to regulate the thermal behaviors between the textile and the human body and provide comfort to the wearer. The PCM packets are placed inside vest pockets, with or without a Velcro fastener, to maintain close contact with the wearer for optimal heat transfer and cooling efficiency (Mekrisuh et al., 2025). PCM enables the efficient transfer of thermal energy without energy consumption. Thus, developing effective strategies to integrate PCM thermal storage technology with wearable devices is crucial for achieving energy sustainability and efficient personal thermal management systems. For instance, Gu et al. (2025) developed a novel cooling vest with

PCM that is strategically placed based on the body’s mapping of thermal sensation and perspiration. Promising results showing that the sustained cooling effect (lasting for up to 2 h) with improved thermal comfort and lower self-perceived level of fatigue by the subjects were presented. However, the limitations of PCM, including low thermal conductivity and leakage issues, have hampered its development and applications used for human cooling. From the user survey conducted (refer to Figure 3) by the authors here, issues relating to weight, condensation, and the long time required for recharging were also highlighted. Researching further beyond this, composite PCMs with enhanced thermal conductivity and stable structure appear to have good potential for human cooling (Yang et al., 2024).

### 2.1.2 Evaporative cooling technologies

Evaporative cooling technologies mainly rely on water or moist air as the coolant to dissipate heat. This technology has the advantage of high heat dissipation, owing to water’s high latent heat capacity and eco-friendly nature. The most straightforward of them all is to use cooling towels or a vest that uses the effect of water

evaporation to draw heat away from the body. The performance of such evaporative cooling vests was investigated by Dehghan and Reza in 2023 (2023). It was found that the use of such evaporative cooling vests can reduce the perceptual and physiological heat strain of construction workers working under hot and dry conditions. Wettable or hydrogel-based fabrics can also be used to enhance evaporation to cool the body down. Although they offer efficient cooling, their performance and efficiency tend to deteriorate when subjected to prolonged sunlight. In addition, vests that make use of evaporative cooling tend to require the vest to be wet, which will therefore also cause the user to be wet and the vest to be heavy. The wet sensation can be uncomfortable for many. Lastly, evaporative vests' performance tends to deteriorate in humid environments, when the evaporation rate is reduced. To this, innovative techniques that can reduce the humidity in the microclimate around the vest need to be introduced. An example is the M-cycle evaporative cooling vest designed by Raad et al., which has a separate channel outside the wet channel to induce air flow, increasing the rate of evaporation (Raad et al., 2019). Separately, innovative, nature-inspired, and smart materials are being developed that can enhance evaporation, which can also contribute to the advancement of such an evaporative cooling vest. For example, membrane-based and vacuum desiccant-based cooling garments are two widely used evaporative methods (Xue et al., 2024) that are used to enhance evaporation. This will be elaborated on in Section 2.1.4.

### 2.1.3 Radiative cooling materials

Radiative cooling and heating offer significant energy savings for human thermal comfort, with excellent energy efficiency (Li et al., 2022). Human skin, with an emissivity over 0.95, effectively radiates heat in the mid-infrared range (7–14  $\mu\text{m}$ ) (Cai et al., 2018; Xue et al., 2024). By designing fabrics to control optical properties like emissivity and reflectance, passive thermal regulation can be achieved based on ambient conditions. However, challenges remain with the reflective appearance and limited comfort of these materials.

A breakthrough in this area is metafabrics, which enhance cooling by radiating heat to the environment. Yan et al. developed a bioinspired metafabric with a dual-gradient Janus design for personal radiative and evaporative cooling (Yan et al., 2025). The dual-gradient Janus design enhances sweat-wicking and evaporative cooling, with a minimal sweat consumption of only 0.5 mL/h needed to maintain a comfortable skin temperature, preventing excessive sweating. Its hierarchical fiber structure achieves an impressive solar reflectance of 99.4% and a mid-infrared emittance of 0.94, leading to a 17.8 °C skin temperature reduction under intense sunlight. Mesoporous silica nanoparticles embedded in the fibrous network absorb moisture from the atmosphere during humid nights and release it during hot days, providing an extra 2.5 °C cooling effect. Additionally, the metafabric offers excellent wearability and a wide range of color options, circumventing the issues raised earlier in terms of appearance and ergonomic comfort for the wearer. Similar findings were also observed in another study by Xue et al. (2024), where their dual-mode Janus Metafabric was designed to be used for both radiative cooling and solar heating. The cooling side, featuring a cellulose acetate@Al<sub>2</sub>O<sub>3</sub> porous coating, boasts a solar reflectance of 92.12%, an infrared emissivity of 83.22%, and a net cooling power of 55.85 W·m<sup>-2</sup>. The heating side, made of

multi-walled carbon nanotubes, achieves a high solar absorption rate of 88.4%. The metafabric also offers excellent ultraviolet resistance, durability, and washing performance, making it ideal for practical use. By simply flipping the fabric, users can easily switch between cooling and heating modes to adapt to changing ambient temperatures. In the drive for sustainability, researchers have also begun looking at radiative cooling materials that are sustainable. A sustainable and biodegradable laminated membrane with integrated radiative cooling and unidirectional sweat absorption capabilities was developed for personal moisture-thermal management (Zhao et al., 2025). This membrane is constructed through a layer-by-layer assembly process using cellulose and hydrophobically modified hydroxyapatite nanowires as the primary building blocks. The design features an asymmetric wettability structure, with a hydrophobic hydroxyapatite inner layer and a hydrophilic cellulose outer layer, enabling unidirectional sweat transport from the skin, through the inner layer, and out to the environment, ensuring moisture comfort for the wearer.

### 2.1.4 Natural and smart fabrics

Janus fabrics with unidirectional liquid transport are effective in removing excess sweat and lowering skin temperature (Min et al., 2024; Xi et al., 2025). However, when the hydrophilic surface reaches its absorption limit, sweat buildup occurs, slowing sweat transport and making the fabric heavy and clingy. Inspired by the Namib Desert beetle and drip tips, (Min et al., 2024), developed a design with circular Coolmax patterns for sweat extraction near the skin and triangular Coolmax patterns for sweat removal on the exterior. This design enhances continuous sweat transport, diffusion, and shedding, reducing skin temperature by 1.3 °C compared to conventional cotton fabric. Additionally, the low adhesion (~0.2 mN cm<sup>-2</sup>) between wet skin and fabric improves comfort.

The porous structure and fiber spacing in fabric design significantly impact comfort and mechanical properties (Hu et al., 2024). Ke et al. (2018) hypothesized that materials capable of transmitting thermal infrared radiation could provide passive cooling without energy input. A nanoporous polyethylene membrane was developed for passive cooling clothing, lowering skin temperature compared to traditional cotton. Meng et al. (2025) created a sandwich-structured nanofibrous (SNF) textile combining radiative cooling, moisture-wicking, and self-cleaning functions. The cooling mid-layer, made of hydrophilic PAN-PVA nanofibers, has a solar reflectance of 97.9% and infrared emittance of 90.8%, while the hydrophobic PPy-PVDF-HFP layer absorbs solar heat with 96% efficiency. Outdoor tests showed that the cooling side of the SNF textile kept simulated skin 8.5 °C cooler than conventional fabric. This combination allows for directional sweat transport, keeping the skin dry and comfortable.

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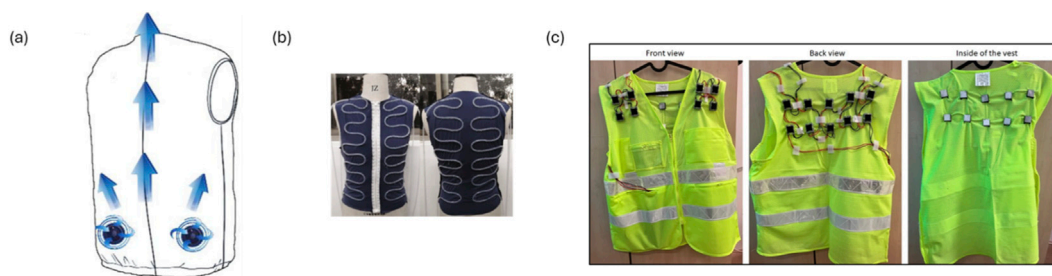


FIGURE 5 (a) Air-cooled garment (Ren et al., 2022), (b) liquid-cooled garment designed by Xu et al (Xu et al., 2023), (c) thermoelectric-cooled garment.

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Most cooling fabrics offer static thermal regulation, limiting their adaptability to fluctuating ambient temperatures. Therefore, there is a need for temperature-responsive fabrics that can adapt to dynamic outdoor environments. Thermal management textiles, with ultralight insulating layers and adaptive cooling technologies, improve temperature regulation in extreme conditions. Moisture management textiles use advanced structures for one-way transport and breathable membranes, enhancing comfort in activewear and outdoor gear (Tian et al., 2025). Xue et al. (2025) developed a fabric that has dynamic thermochromism (visible light regulation capability of 59%) and reversible moisture transport. Under hot environmental conditions, the fabric reflects sunlight and shifts to a hydrophobic inner and hydrophilic outer state, promoting sweat conduction and evaporation to keep skin dry and comfortable. Lan et al. (2025) designed a kirigami-inspired fabric that captures solar energy for heating in low sunlight and creates heat-dissipation channels during perspiration, demonstrating superior adaptability compared to static fabrics.

## 2.2 Active cooling technology for personal cooling devices

Active cooling technology regulates body temperature using external energy sources, such as batteries, electricity, and thermoelectric devices (Tabor et al., 2020). The challenge is to create efficiency, energy-powered cooling solutions for human cooling in various environments, including workplaces, military settings (Zhang and He, 2024), sports, and even daily life (simply as personal climate comfort). This review explores three main active cooling technologies: (i) air-cooling garments (ACGs), (ii) liquid cooling garments (LCGs), and (iii) thermoelectric cooling garments (TECGs).

### 2.2.1 Air-cooling garments

Air-cooling garments (ACGs), illustrated in Figure 5a, use small battery-powered fans or air circulation units to create a

microclimate between the body and clothing. These systems circulate air around the body to remove heat and moisture, promoting heat dissipation. ACGs are lightweight and portable, with no need for excessive tubes or pumps, making them suitable for various occupations and applications. The cooling performance of ACGs depends on the ventilation unit, air gap between the skin and fabric (Zhao et al., 2022), eyelet design, fabric permeability (Zhao et al., 2023), and the integration of fan units to ensure efficient air movement and moisture transport. Proper fan placement and airflow distribution across the body enhance evaporative heat loss and cooling (Del Ferraro et al., 2022). However, fan placement may result in uneven cooling, and ACGs may be less effective in extremely humid environments (Wenfang et al., 2024).

There exist air-cooling garments in the market today, exemplified by the Venture Heat fan vest surveyed as presented in Figure 3. However, it is unlikely that air-cooled units can provide sufficient cooling for thermal comfort by themselves, as also shown with the user survey conducted in Figure 3. Rather, the integration of air-cooling technology with other technologies, such as TEC (to be elaborated in Section 2.2.3) or passive cooling technology such as phase changing material or evaporative fabric design (see Section 2.1) seems to be more promising. An example is the wearable cooling and dehumidifying system (WCDS) designed by Lou et al. (2022). The team showed that, as compared to pure air-cooling garments, WCDS provided an additional 4 to 6 °C drop in cooling temperature, and a mean cooling power of more than 5 times that provided by air-cooling garments. In their review paper published in 2024, Xu et al. also noted the superior performance of hybrid vests incorporated with PCM packs and air-ventilation fans (Xu et al., 2024). Numerous experimental studies have validated the superior performance of such hybrid vests by enhancing evaporative cooling and convective heat transfer using air ventilation within the clothing microclimate. (Lu et al., 2015; Chan et al., 2017; Wang et al., 2020). Hence, it is expected that future research in this area will likely centre on the optimization of air-cooling unit designs in combination with other technologies. Factors such as weight and vibration stemming from the incorporation of air-cooling fans must also be addressed (Xu et al., 2024).

### 2.2.2 Liquid cooling garments

Liquid cooling garments (LCGs), which normally use water, can be more effective in removing heat when compared to air cooling garments due to the greater heat conductivity and thermal capacity of water than air. The cooled liquid will be circulated through a

network of tubes over the skin surface to absorb the body's heat dissipation, as seen in [Figure 5b](#). Originally designed for astronauts in hostile space conditions, the weight of the entire garment was not a consideration during the design process ([Tokizawa et al., 2020](#)). Increasingly, this has been used in other applications, such as for pilots ([Xu et al., 2023](#)), soldiers ([Jovanović et al., 2012](#)), firefighters ([Yang et al., 2023](#)), and for other uses such as protective gear. Results show that using such garments helps maintain significantly lower body skin temperature ([Cvetanović et al., 2021](#)) and reduces the physiological strain caused by physical exertion, with significant benefits in nearly all the physiological parameters tested ([Jovanović et al., 2012](#); [Zheng et al., 2022](#); [Yang et al., 2023](#); [Zhang et al., 2024a](#)). LCGs are always dependent on the liquid's temperature and flow rate, accompanied by a complex configuration and network of tubes embedded within the clothing to circulate and distribute the chilled liquid ([Xu et al., 2023](#)), effectively reducing body and skin temperature. These systems typically rely on a refrigeration unit, pumps, or ice packs to maintain the cooling effect. By varying the liquid temperature and arrangement of the tubes, [Xu et al. \(2023\)](#) have observed that localized cooling at specific parts of the body can be optimized.

Due to their weight penalty and reliance on pumps or compressors, LCGs have not been extensively explored. Thus, LCG still has much space for improvement and optimization (such as the inlet liquid temperature, conductivity properties of the pipes, and ability for intermittent cooling). [Zheng et al. \(2022\)](#) in their numerical work proposed that intermittent cooling could be an effective way to be employed, given its lower power consumption while ensuring that thermo-physiological comfort can still be maintained. [Zhang et al. \(2022\)](#) proposed to cool the liquid by using a thermoelectric conductor—showing potential that similar cooling effects can be achieved, but at a much lower weight penalty. This highlights the potential of hybrid PCD systems with the incorporation of liquid cooling technology.

### 2.2.3 Thermoelectric cooling garments

Thermoelectric cooling (TEC) garments (TCGs) use the Peltier effect, where an electrical current creates a temperature differential that absorbs heat and dissipates it externally. Thermoelectric devices (TEDs) are solid-state refrigeration devices offering adjustable cooling power, a lightweight design, and temperature control ([Feng et al., 2024](#); [Yusuf et al., 2022](#); [Ang et al., 2022](#)). CGs provide advantages over air-cooling and liquid-cooling garments, including portability, zero emissions, precise temperature control, no noise pollution, and no need for liquid media ([Chen et al., 2022](#); [Sun et al., 2022](#)). A sample TCG is seen in [Figure 5c](#). TEDs are evaluated on parameters like coefficient of performance, cooling capacity, temperature difference, and cooling heat ([Sun et al., 2022](#)). While promising for wearable personal thermoregulation, challenges remain, particularly in dissipating heat from the TED's hot side, which can affect cooling performance. Optimizing TED integration in garments and ensuring efficient heat dissipation are key areas for improvement. Effective placement of TEDs targeting key body areas has shown notable cooling benefits ([Wenfang et al., 2024](#)). However, achieving optimal design and testing for TED-based garments in high-temperature environments remains crucial for enhancing comfort and cooling capacity ([Wang et al., 2025](#)).

In the following subsections, we highlight major technological gaps identified in this area. First, there is a need to redesign the structure of TEC for effective cooling against human skin. Second, the primary challenge is their lack of flexibility, as most TECs are built on rigid substrates, making them unsuitable for wearable applications. Additionally, TECs must efficiently dissipate both parasitic Joule heat and pumped heat to sustain the Peltier effect on the cold side. While bulky heat sinks can improve heat dissipation and enhance cooling performance, their size and weight make them impractical for personalized wearable devices. Lastly, the thermal efficiency of TEC is notoriously low. It is envisaged that a revolutionary increase in thermal efficiency is only possible through the discovery of new thermoelectric materials to increase the materials' Seebeck coefficient, while maintaining high electrical conductivity and low thermal conductivity.

#### 2.2.3.1 Redesigning the structure of thermal electric cooling devices for cooling against human skin

Current TECs available in the market are mostly optimized for use in electronics, where the microclimate features low thermal resistance. As such, there is a need to re-examine the structure of TEC, specifically their fill factor, that is, the ratio of the semiconductor legs to that of the substrate, and the number of stages, when the TEC is applied in a high thermal resistance environment, such as against human skin ([Ang et al., 2024](#)). [Krishna and Manikandan \(2024\)](#) incorporate pores into the thermoelement to enhance the thermal performance of the TEC. The results indicate that, under identical boundary conditions with varying input currents, the presence of pores in the thermoelement not only lowers the cold side temperature of the TEC by 4–9 °C, but also reduces the required length to achieve the same cold side temperature. In addition, three pore orientations—horizontal, vertical, and slanting—are examined, with the horizontal orientation exhibiting the best thermal performance. [Kishore et al. \(2019\)](#) show in 2019 that TEC designed for cooling wearables needs to have a low fill factor and high aspect ratio ([Kishore et al., 2019](#)). [Ang et al. \(2022\)](#) provided a detailed analysis of multi-stage thermoelectric coolers (TECs) for wearable cooling applications. While traditionally used for high-temperature differentials, the study demonstrates that for the first time, multi-stage TECs can significantly enhance cooling performance against human skin while maintaining efficiency comparable to single-stage TECs. Using a 1D analytical model, computations confirmed the superior cooling capability of multi-stage TECs. Beyond theoretical analysis, the study also employed a validated finite element analysis (FEA) with experimental data, addressing a gap in current literature regarding TEC validation. The findings indicate that at low current levels, relevant to wearable cooling, the 1D model accurately predicts TEC behavior. A parametric study identified key factors affecting multi-stage TEC performance, including the number of stages, current ratio, fill factor, aspect ratio, and leg area. These insights contribute to optimizing TEC designs for efficient, skin-contact cooling applications. In a similar work, [Ren et al. \(2024\)](#) also used a multi-layered structured but, coupled with the design and fabrication of a highly thermally conductive and flexible heatsink for a wearable TEC wristband, achieving a large temperature drop (8.8 °C) for an imitated on-body test and a 13.1 °C temperature

decrease in air. The well-designed functional composite layer, including phase change material, thermally conductive fillers, and metal foam, can establish an effective equilibration among cooling performance, thermal management capacity, and mechanical properties. Notably, an interesting study by [Xu et al. \(2022\)](#) achieved a large active temperature drop with cooling capacity ( $>10\text{ }^{\circ}\text{C}$  and  $>256\text{ W/m}^2$ ) by designing a film-based flexible thermoelectric cooler using an innovative quadra-layered structure and a vortex generator (VG). The quadra-layered structure is electrically connected in series, which pumps more heat per area than the traditional single-layered structure. In addition, the air vortices induced by the VG enhance heat dissipation from the hot surface of the device, leading to better cooling performance.

### 2.2.3.2 Flexible thermoelectric cooling devices

Flexible TEDs can make conformal contact with the skin to provide direct cooling without bulky heat sinks or a coolant ([Feng et al., 2024](#)). Most studies, however, have been limited to a single TED over a relatively small surface area on the skin (such as the arm). For example, [Wei et al. \(2022\)](#) designed an optimized (using both theoretical analysis and Finite Element Analysis (FEA)) wearable TED with a pin-fin soft cover that was placed on the human arm, cooling the skin and recording a temperature drop of  $1.5\text{ }^{\circ}\text{C}$ . ([Sivarenjini et al., 2021](#)). developed a high-performance flexible and wearable TED with Phase Change Material (PCM) heatsinks and semi-LMinterconnectors. With excellent flexibility and stretchability, the proposed design was able to achieve a cooling temperature of  $10\text{ }^{\circ}\text{C}$  at ambient temperatures of  $24\text{ }^{\circ}\text{C}$  and  $35\text{ }^{\circ}\text{C}$ , supported by different PCMs. Notably, [Feng et al. \(2024\)](#) integrated 16 small individual TEDs onto a high thermal conductivity Dyneema fabric ([Candadai et al., 2021](#)) covering approximately a total surface area of  $400\text{ cm}^2$ . Arranging the individual rigid TED in the garment allows good flexibility and demonstrates rapid cooling (within 3 min) of the skin. In recent years, benefitting from the rapid development of conductive polymers, flexible TECs based on organic TE (OTE) materials have come into focus. [Newby et al. \(2025\)](#) reported on a proposed knitted, textile-based cooling garment that does not require a heat sink to function. The garment features a double jersey knit with specific courses of knit containing the conductive pathways for both Seebeck and Peltier effects. The knitted structure is kept securely in place on the human through knitted elastic courses. The device shows excellent thermoelectric generation of  $7.48\text{ mV}$  and  $0.46\text{ mA}$  at a temperature difference of  $12.5\text{ }^{\circ}\text{C}$ . [Gao et al. \(2024\)](#) developed a honeycomb wearable thermoelectric cooler, which not only reduced the heat leakage of the device but also brought about flexible support as a wearable for the human body. The cooling effect was also significant, showing a temperature difference of  $6.5\text{ }^{\circ}\text{C}$  compared to the outdoor environment. Although organic TE materials have been widely considered to possess good flexibility, more research will need to focus on fabricating ultrathin, wearable, and stretchable devices. To satisfy the requirement of a flexible cooling device, searching for electrode materials with high conductivity and good bendability is equally vital. Stretchable multilayer graphene/graphene scrolls or organics with high conductivity show promising results in flexible electronics, which might have strong potential for sophisticated cooling applications ([Ding et al., 2021](#)).

### 2.2.3.3 Light and flexible heat sink designs

The role of heat sinks is to maintain the stable temperature of the hot side of TECs and avoid overheating and damaging TECs at high temperature differences. Most TECs provide a large cooling performance with the assistance of rigid heatsinks and electrodes, thus limiting wearability and practical implementation. [Li et al. \(2024\)](#) proposed and came up with a flexible bridged personal TEC with a flexible heatsink to enhance the thermal conduction, achieving the desired thermal comfort. [Zheng et al. \(2022\)](#) presented a wearable TEC integrated with a dual-layer heatsink system composed of hydrogel and nickel foam to address the relatively large thermal resistance between the cool side of the TEC heatsink. The high thermal conductivity of nickel foam enables efficient heat transfer from the thermoelectric cooler to the heatsink, while the strong adhesion between the hydrogel and nickel foam ensures effective heat dissipation. Additionally, this device exhibits excellent flexibility due to its discrete heatsink structure, with a minimum bending radius of  $7.5\text{ mm}$ . Whether in a flat or bent state, it achieves a significant and sustained temperature reduction of approximately  $10\text{ }^{\circ}\text{C}$  at an input current of  $0.3\text{ A}$ . During on-body testing, the device demonstrated a stable  $7\text{ }^{\circ}\text{C}$  cooling effect that can be powered by a single AA battery. [Ang et al. \(2024\)](#) proposed in the numerical and experimental study that PCM can be used as part of the heat sink design to dissipate the heat away while ensuring  $\text{COP}_{\text{max}}$  can be attained. The study concludes that for efficient and sustainable TEC operation, the PCM's liquid fraction should be maintained below 40%. To achieve continuous and sustainable performance, future work should explore intermittent operation strategies, optimized finned designs, and enhanced PCM volume and phase change temperature configurations to improve heat dissipation and charging efficiency, paving the way for further advancements in PCM-integrated TEC systems. [Ding et al. \(2024\)](#) pushes the boundary further by introducing a flexible PCM heat sink specifically for wearable TE devices. The flexible PCM heat sink consists of integrating Paraffin and graphene with silicone rubber, resulting in a composite material with excellent heat absorption ability. The sealing rubber prevented the Paraffin from leaking during the phase change process, while the incorporation of graphene enhanced the thermal conductivity of the composite, improving its overall thermal management capabilities. This significantly enhances heat dissipation efficiency and boosts the overall performance. Through this, the TE module successfully achieved a sustained cooling of  $11.21\text{ }^{\circ}\text{C}$  with long cooling durability of at least 300s, ensuring long-lasting comfort. [Li et al. \(2024\)](#) have a similar flexible heatsink design that is made up of metal foam, phase change material, and fin structure, again showing good promise in the thermal performance.

### 2.2.3.4 Innovating new materials to improve the efficiency of thermoelectric cooling devices

In the market, the most commonly used thermoelectric material is Bismuth Telluride ( $\text{Bi}_2\text{Te}_3$ ) for both p and n legs, amongst others such as Lead telluride ( $\text{PbTe}$ ) and Silicon germanium ( $\text{SiGe}$ ) based semiconductors ([Krishna and Manikandan, 2024](#); [Liu et al., 2024](#)). As one of the earliest known thermoelectric semiconductors,  $\text{Bi}_2\text{Te}_3$ -based alloys have dominated commercial thermoelectric materials for over half a century. After years of continuous research, the ZT (a

dimensionless figure of merit that is used to assess the performance of TE materials) value of commercially used  $\text{Bi}_2\text{Te}_3$  materials has now approached 1.0 at room temperature. However, recent in-depth studies on this material system have revealed that the potential for further enhancing the thermoelectric performance of  $\text{Bi}_2\text{Te}_3$  is quite limited (Wang et al., 2024). As such, much research is increasingly focused on developing  $\text{Bi}_2\text{Te}_3$  alloys, or alternative and/or novel materials to improve the efficiency of thermoelectric cooling devices. The recently discovered n-type  $\text{Mg}_3\text{Bi}_{2-x}\text{Sb}_x$  represents encouraging progress for such an exploration, though its average ZT value remains similar to that of commercial n-type  $\text{Bi}_2\text{Te}_{3-x}\text{Se}_x$  (Mao et al., 2021). Using a hot extrusion manufacturing process, Zhang et al. (2024b) were able to manufacture a novel n-type polycrystalline  $\text{Bi}_2\text{Te}_3$  system with a nominal composition of  $\text{Bi}_2\text{Te}_{2.8}\text{Se}_{0.2}\text{S}_{0.01}$ . This material has an ultrahigh power factor ( $51 \mu\text{Wcm}^{-1}\text{K}^{-2}$ ) with improved charge carrier transport mobility ( $150 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ ) resulting in a temperature difference of 73.9 K. Lead telluride (PbTe) are increasingly being research on, given that they possessed a cubic rock-salt crystal structure that is stronger mechanically than layered  $\text{Bi}_2\text{Te}_3$ . Achieving similar outcomes to that of (Zhang et al., 2024b) with improved charge carrier transport mobility, Liu et al. (2024) did the work differently by fabricating PbTe ingots which are then used to fabricate the thermoelectric cooling device, achieving a maximum cooling temperature difference of about  $14^\circ\text{C}$  to  $28^\circ\text{C}$  at room temperature and ambient temperature of  $77^\circ\text{C}$  respectively. The first thermoelectric cooling device utilizing n-type PbS (Lead chalcogenide) was fabricated by Wang et al. (2024). This cost-effective and earth-abundant n-type PbS material compound with outstanding thermoelectric performance was optimized, achieving a record-high ZT of 0.64 at room temperature with an impressive cooling temperature difference of approximately  $36.9^\circ\text{C}$  at room temperature.

### 2.3 Hybrid cooling technology for personal cooling devices

Looking beyond the above two (passive and active) cooling technologies individually, there is an increase in interest in hybrid models (Figure 4). Designing hybrid personal cooling systems (HPCSs) that combine two or more cooling methods, such as PCM-fan suits or air-liquid cooling garments (Rahimi et al., 2024). Studies on thermal manikins showed that hybrid cooling garments provide greater and longer-term cooling effects compared to single cooling methods. For example, Chan et al. (2019) investigated the effectiveness of a hybrid cooling vest using a frozen gel as a passive cooling method to conduct the thermal heat away, coupled with air ventilation to improve evaporation and convective rate to increase heat losses. Results were promising, showing that exercise performance was indeed maintained. Cooling garments can also integrate thermoelectric devices with fans (using convection and evaporation) to provide continuous cooling by delivering pre-cooled air to the body. This hybrid system is lighter, more reliable, and allows for adjustable air temperature and speed, offering advantages over PCM-Fan (using conduction and evaporation) hybrid cooling garments. Chen and Zhang (2024) did a comparison of the above two hybrid

configurations and found that both are able to reduce heat stress on the human body in high temperatures. The hybrid thermoelectric-fan configuration is much lighter and cooled over a longer period and exhibited very good humidity regulation performance as compared to the PCM-fan configuration, where cooling performance was optimal only for the first 30 minutes. Thermoelectric devices can also be combined with a liquid cooling medium, such as in the case of a thermoelectric-water hybrid cooling garment that is composed of a TEC, a pump to drive water flow through the cooling garment, and a cooling garment (including water tubes that are sewn inside the basic garment) is proposed. This allows sufficient contact and heat exchange between the human body and the water-cooling media. With a proper inlet temperature of the fluid, thermal comfort can be maintained with energy savings on the TEC.

### 2.4 Thermal assessments for personal cooling devices

Thermal assessments today are largely designed for space cooling, where thermal comfort is assessed to be high if a uniform and constant indoor thermal environment within a narrow range is achieved (Tang et al., 2022). For example, ASHRAE Standard 55 on the Thermal Environmental Conditions for Human Occupancy (American Society of Heating, 2021), provides guidelines on the determination of requirements for thermal comfort using a combination of metabolic rate assumption of the human, clothing insulation, air temperature, radiant temperature, airspeed, and humidity of an indoor space. The ISO 7730:2005 standard (ISO 7730, 2005) also provides guidance on computing thermal comfort based on similar requirements. However, such thermal assessments cannot be applied to PCD, especially for PCD, which provides localized cooling to certain parts of the human body.

In recent years, some standards have emerged that are associated with the thermal assessment of PCD. The first is ASTM F2371-16, which provides a standard test method for measuring the heat removal rate of personal cooling systems using a sweating heated manikin (ASTM F2371-16, 2016). The use of ASTM F2371-16 can provide a way to quantify cooling provided by different PCDs with a common base ensemble. However, cooling performance quantified using a thermal manikin has been known to be inconsistent, with significant variations in cooling performance reported with the use of different test protocols. Kim et al. (2024) evaluated five commercial PCDs with three different testing protocols using thermal manikins, including the ASTM F2371-16. It was found that, as the ASTM F2371-16 mandates testing under hot and dry conditions, the cooling performance is often overestimated. Similar conclusions were made by Bogerd et al., in 2010, where it was explained that the thermal manikin often assumes constant skin temperatures, resulting in a typical over-estimation of cooling performance compared to actual human skin, which changes due to the vasoconstriction response (Bogerd et al., 2010).

Another standard that can be considered is the ASTM F2300-10 (ASTM F2300-10, 2022), which uses physiological testing to measure the performance of personal cooling systems through user trials. Measurements include core temperature, mean skin

TABLE 1 Comparative analysis of different space cooling solutions, including complementary technologies.

System	Performance	Efficiency	Sustainability	Techno-economic feasibility
Conventional VC cycles	High COP (3–6), Max. cooling $\Delta T$ (20–30 °C)	Among the best (COP 3–6)	Dependent on refrigerants (shift to natural refrigerants improves, but with safety risks); active cooling	Most mature, cost-effective, globally dominant; lifespan ~15 years
Magnetocaloric cooling	COP (0.1–1), Max. cooling $\Delta T$ (2–10 °C)	Potentially high COP (lab-scale competitive with VC)	No refrigerants; rare-earth dependency a concern; active cooling	Early R&D; high material cost; not yet viable at scale; lifespan ~10 years
Electrocaloric cooling	COP (0.1–1), Max. cooling $\Delta T$ (2–10 °C)	High COP possible (esp. Regenerative cycles)	No harmful refrigerants; benign materials; active cooling	Limited scalability beyond niche markets; high material costs; lifespan ~10 years
Elastocaloric cooling	COP (0.1–1), Max. cooling $\Delta T$ (2–10 °C)	Comparable to VC in prototypes; multistage is better	Solid-state, safe, refrigerant-free; active cooling	Alloys are costly; fatigue and scalability issues; lifespan ~10 years
Electrochemical cooling	COP (0.3–2), Max. cooling $\Delta T$ (5–15 °C)	Lower power use than thermoelectric; moderate efficiency	Benign electrolytes; stability issues remain; active cooling	Niche (wearables, biomedical); not feasible for large-scale; lifespan ~8 years
Thermionic cooling	COP (0.3–2), Max. cooling $\Delta T$ (5–15 °C)	Efficiency improving with nanomaterials	No refrigerants; some material toxicity risks; active cooling	Very experimental; not close to commercialization; lifespan ~10 years
Thermoelectric cooling	COP (0.3–1), Max. cooling $\Delta T$ (2–10 °C)	Low efficiency	No refrigerants; costly; active cooling	Commercialized; however, still costly; lifespan ~10 years
Membrane heat pumps (MHPs)	COP (1–3), Max. cooling $\Delta T$ (10–20 °C)	Simulated COP 10–40; prototypes <3 due to pump inefficiency	Uses only water → excellent sustainability; active cooling	Promising, but scaling, fouling, and pump efficiency require further development; lifespan ~12 years
Radiant cooling systems	Max. cooling $\Delta T$ (~10 °C)	Energy savings up to 50%	Passive/low-energy; sustainable if condensation is controlled	Already used in landmark buildings, adoption is limited by the climate; lifespan ~20 years
District cooling (DCS)	COP (4–6), Max. cooling $\Delta T$ (~7 °C)	30%–50% energy savings; load sharing improves efficiency	Lower GHG footprint; stronger with renewables/TES; active cooling	Proven in the Gulf cooperation council region; high CAPEX but cost-effective in dense cities; lifespan ~30 years
Cool roofs and cooling paints	Max. cooling $\Delta T$ (~8 °C)	Cuts cooling load by 20%–30%	Highly sustainable, reflective, and durable; passive cooling	Very low cost; already widely deployed; lifespan ~15 years
Green roofs/walls	Max. cooling $\Delta T$ (~7 °C)	Energy savings 20%–80% depending on design	Strongest sustainability (ecosystem, shading, carbon benefits); passive cooling	Moderate installation/maintenance cost; feasible for urban retrofits; lifespan ~15 years; plant replacement cycle 3–10 years

temperature, heart rate, exposure time, oxygen consumption, and whole body sweat rate. While no thermal manikin is used in this test method, the standard only mandates testing in a single environment, which may not be representative of the actual environment used (Bach et al., 2020). The standard also recommends the use of 4, 8, or 14 site measurements to compute mean skin temperature measurements. However, the use of PCD often creates non-uniform skin temperature distribution, and the use of discrete and a low number of measurement sites may not be representative of the efficacy of the PCD (Bach et al., 2019).

Hence, researchers often defer to self-designed protocols to compare the efficacy of PCD. For instance, Tang et al. compared six different types of PCD by using a climate chamber, where the test subject is put through experiment-rest cycles, and their thermal comfort was evaluated with questionnaires and skin temperature measurements (Tang et al., 2022). A similar customized testing protocol was also designed by Tang et al. in 2021, which includes a combination of subjective assessments and

measuring multiple physiological parameters such as skin temperature, heart rate, and salivary-alpha-amylase (Tang et al., 2021). Zhou et al. in 2024 also customized a protocol of measuring core temperature, mean skin temperature, heart rate, and user assessment of thermal sensation, wetness sensation, and thermal comfort to evaluate the effectiveness of PCD (Zhou et al., 2024).

It can therefore be seen that for further advancement in the field of PCD design, there is a need for a simple, objective, and affordable test to evaluate the thermal comfort of PCD (Martinez-Albert et al., 2023). Recommended physiological parameters and subjective assessments, and the method of measurement, needs to be researched upon to provide a guideline for researchers to benchmark against when evaluating different PCD designs. The recommended guidelines should also be designed with simplicity and affordability in mind for widespread adoption. Another critical aspect of the guideline is the requirement of a testing envelope that considers different climatic conditions for evaluation.

### 3 Sustainable space cooling solutions

While PCDs offer great potential in reducing the energy consumption of space cooling, they are unlikely to completely replace it. Therefore, sustainable space cooling solutions beyond traditional VC cooling cycles are becoming more important (Elnagar et al., 2023). This review focuses on these alternatives, aiming to reduce energy use and environmental impact. It begins with a summary of VC cooling cycle evolution, followed by a review of promising alternatives like solid-state cooling cycles, membrane heat pumps, and radiant cooling systems. The section concludes with a discussion on complementary technologies, such as district cooling, cooling paints, and other methods that can reduce the energy costs of large space cooling. Table 1 summarizes the comparative analysis of the different space cooling solutions reviewed in this paper.

Previous comparative studies have shown that vapor-compression systems remain difficult to surpass in efficiency (El Fil et al., 2021; Abedrabbah et al., 2022). Our review corroborates these findings but further demonstrates that emerging technologies such as membrane heat pumps and radiant cooling, when combined with district-scale integration, can deliver comparable system-level efficiency with substantially lower environmental impact.

#### 3.1 Evolution of VC cooling cycles

Conventional vapour-compression (VC) cycles for space cooling are the main go-to technology providing thermal comfort globally. However, the large energy consumption and use of non-environmentally friendly refrigerants necessitate sustainable alternatives. Few other cooling cycles, however, provide space cooling more efficiently than the VC cycle. For instance, El Fil et al. performed a quantitative comparison of 14 space-cooling technologies that include two-phase technologies, gas cycles, and solid-state technologies. They found that VC has superior performance, in terms of coefficient of performance (COP), exergetic efficiency, and power density, when compared to all other alternative cooling technologies (El Fil et al., 2021). In a recent review by Abedrabbah, VC still achieved the highest sustainability score, which includes various parameters such as COP, scalability, maturity level, and others (Abedrabbah et al., 2022). Hence, VC cycles are likely to remain dominant unless an alternative cycle with higher energy efficiency emerges. To increase the sustainability index of VC cycles, there are many developments in environmentally friendly refrigerants to replace current harmful refrigerants. An emerging option is the use of natural refrigerants such as hydrocarbons (HCs) (Ibrahim et al., 2024), which have good thermophysical properties, do not deplete the ozone layer, but carry the added risk of flammability that must be managed. These include R290, R600 and RE170 as examples (Calleja-Anta et al., 2024). To manage its flammability risk, research on binary and ternary mixtures involving HCs is also increasing (Kumma and Kruthiventhi, 2024).

Other technologies that have the potential to address the drawback of VC cooling cycles include solid-state cooling solutions, membrane heat pumps, and radiant cooling systems,

all of which will be discussed in more detail in the subsequent sub-sections.

#### 3.2 Solid-state cooling solution

Solid-state cooling technologies, such as magnetocaloric, electrocaloric, elastocaloric, electrochemical, and thermionic cooling, have gained significant attention as sustainable alternatives to conventional vapor compression systems. These technologies leverage caloric effects and reversible temperature changes in materials under external fields (magnetic, electric, or mechanical stress) to achieve cooling without the use of harmful refrigerants. Solid-state cooling systems offer several advantages, including compact design, high energy efficiency, and environmental friendliness.

##### 3.2.1 Magnetocaloric cooling

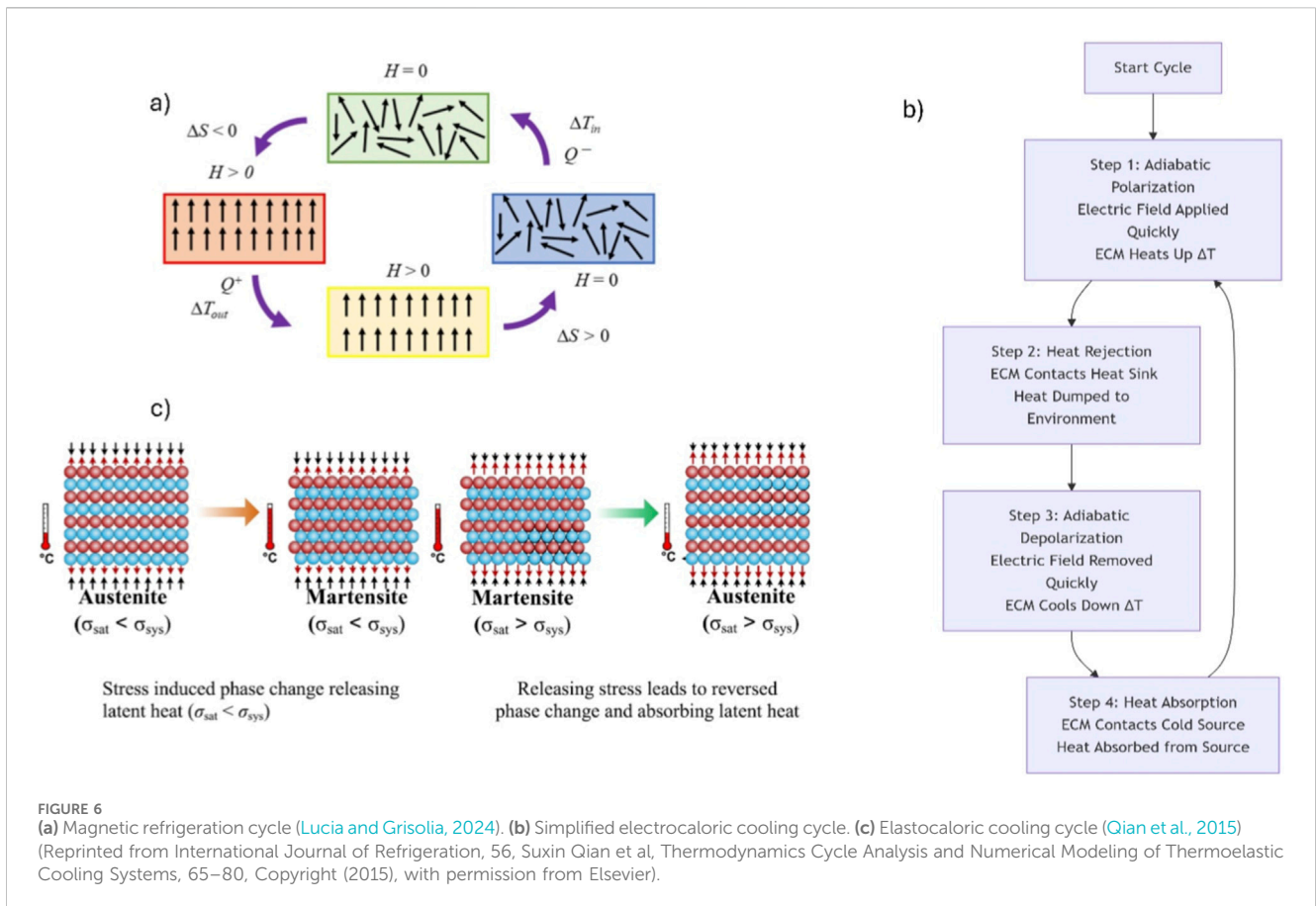
Magnetocaloric cooling relies on the magnetocaloric effect (MCE), where certain materials experience a temperature change when subjected to a varying magnetic field. This phenomenon has gained significant interest due to its potential for environmentally friendly and energy-efficient refrigeration applications (Das, 2024). Among magnetocaloric materials, gadolinium and its alloys have been widely studied due to their strong magnetocaloric properties. However, challenges such as high cost, oxidation susceptibility, and limited temperature range have led researchers to explore alternative materials, such as La-Fe-Si family and Mn-Fe-P-As compounds, which exhibit large entropy changes and enhanced performance (Mellari, 2023). The key advantages of magnetocaloric cooling include the absence of refrigerants, reduced energy consumption, high reversibility, and near-silent operation, making it a viable alternative for industrial and household cooling applications (Owolabi, 2023; Hamad and Alamri, 2024).

Computational models have played a crucial role in optimizing magnetocaloric materials. Techniques such as support vector regression and extreme learning machines have been employed to predict magnetic entropy changes and relative cooling power, allowing for better material selection without extensive experimental testing (Shamsah, 2024). These advancements are paving the way for the practical deployment of magnetocaloric cooling systems.

For practical implementations of magnetocaloric cooling, researchers should focus on advancements in high-entropy alloys, the use of rare-earth-free magnetocaloric materials, and nanostructured composites to improve the magnetocaloric effect and thermal conductivity. Optimizing regenerative cycle designs, such as active magnetic regenerators, and integrating novel heat transfer fluids can enhance cooling efficiency. Developing low-cost, scalable synthesis methods and improving the durability of materials will support commercial adoption. Additionally, hybrid cooling approaches that combine magnetocaloric and other solid-state cooling techniques are being explored to achieve higher coefficients of performance (COP) and broaden application potential. Figure 6a shows a simplified magnetocaloric cooling cycle.

##### 3.2.2 Electrocaloric cooling

Electrocaloric cooling is another promising solid-state cooling technology based on the electrocaloric effect (ECE), where dielectric



materials undergo temperature changes under an applied electric field. The discovery of giant ECE in ferroelectric ceramics and polymers has fueled research into electrocaloric refrigeration as a viable alternative to vapor compression systems (Najmi et al., 2022). Electrocaloric materials, such as Ba (ZrxTi1-x)O3 ceramics, have demonstrated significant temperature variations, making them ideal for compact and efficient cooling devices (Qian et al., 2018). The absence of moving parts, high coefficient of performance (COP), and compatibility with microelectronics highlight the potential of ECE-based cooling for applications ranging from wearable devices to industrial refrigeration (Bai et al., 2023).

To enhance electrocaloric cooling efficiency, advanced thermal management techniques, such as active regenerative (AER) cycles and microfluidic cooling, have been proposed. These approaches optimize heat transfer, allowing for continuous cooling cycles and improved energy utilization (Shi et al., 2019). Further integration with energy recovery systems and scalable device architectures could drive the widespread adoption of electrocaloric cooling in future refrigeration technologies (Cai et al., 2023; Metzdorf et al., 2024).

Some of the research directions are on developing electrocaloric materials with higher adiabatic temperature changes and improved thermal stability through advanced ferroelectric polymers, ceramics, and multilayer structures. Enhancing the energy efficiency of electrocaloric cooling cycles by optimizing electric field application, minimizing hysteresis losses, and improving thermal management techniques is also crucial. Additionally, research is

directed toward scalable fabrication methods for practical implementation, integrating electrocaloric cooling into hybrid cooling systems, and exploring miniaturized solid-state cooling applications for electronics, biomedical devices, and wearable technology. Figure 6b shows a simplified electrocaloric cooling cycle.

### 3.2.3 Elastocaloric cooling

Elastocaloric cooling is based on the stress-induced phase transformation of certain materials, primarily shape memory alloys such as Ni-Ti-based alloys. When an elastocaloric material is subjected to tensile or compressive stress, it undergoes a phase transformation from austenite to martensite, releasing latent heat. Upon unloading, the material reverts to the austenitic phase and absorbs heat, resulting in a cooling effect. This process is analogous to adiabatic demagnetization in magnetocaloric materials, but operates through mechanical stress rather than magnetic fields (Schmidt et al., 2015). The performance of elastocaloric cooling largely depends on the material’s mechanical and thermal properties. Ni-Ti-based shape memory alloys are among the most studied due to their large latent heat, high mechanical strength, and excellent reversibility. Other promising materials include Cu-based SMAs and high-entropy alloys that exhibit improved fatigue resistance and efficiency (Cissé and Asle Zaem, 2020). One effective approach to enhancing elastocaloric performance is optimizing material composition and microstructure, with a focus on minimizing mechanical hysteresis and improving energy efficiency (Zhang et al., 2022).

Several prototype elastocaloric cooling systems have been developed to evaluate their practical feasibility. Most systems employ cyclic loading and unloading mechanisms, such as rotary or linear actuators, to drive the elastocaloric effect. The heat exchange efficiency of these systems is a critical factor influencing their overall performance. A study has shown that a better coefficient of performance can be achieved by a multistage elastocaloric refrigeration system (Snodgrass and Erickson, 2019). Despite its promise, elastocaloric cooling faces several challenges that must be addressed to enable widespread adoption. One major issue is fatigue failure, as repeated stress cycling can lead to material degradation and reduced performance over time. Researchers are investigating strategies to enhance the fatigue resistance of SMAs through alloy design and surface treatments. Another challenge is the development of efficient heat exchange systems to maximize the cooling effect and minimize energy losses. Future research directions include exploring new materials with higher elastocaloric effects, integrating elastocaloric cooling systems with other solid-state refrigeration technologies, and developing scalable manufacturing processes. Additionally, efforts to model and optimize the thermomechanical behavior of elastocaloric materials using machine learning and computational simulations are expected to accelerate progress in the field (Gao et al., 2024). Overcoming challenges related to mechanical fatigue, cost, and scalability will be crucial for the commercialization of elastocaloric cooling in refrigeration, electronics, and thermal management applications. Figure 6c shows a simplified elastocaloric cooling cycle.

### 3.2.4 Electrochemical cooling

Electrochemical cooling, utilizing endothermic ion transport and redox reactions, presents an innovative alternative with the potential for compact, efficient, and flexible integration into wearable systems. As a solid-state cooling solution, it operates by utilizing ion migration and reversible redox reactions to absorb and dissipate heat. The core mechanism involves an external voltage driving ion movement between electrodes *via* an electrolyte, with heat absorption occurring at one electrode and heat dissipation at another (Abdollahipour and Sayyaadi, 2022). By carefully selecting electrode materials, separators, and electrolytes, the cooling effect can be optimized for prolonged and controllable thermal regulation.

The electrode materials play a crucial role in facilitating redox reactions and ion exchange, with commonly used options including metal oxides such as vanadium oxide ( $V_2O_5$ ), manganese oxide ( $MnO_2$ ), and nickel oxide (NiO). Carbon-based materials like graphene, carbon nanotubes (CNTs), and activated carbon offer high conductivity and flexibility, making them suitable for wearable applications. Conducting polymers such as polyaniline (PANI), polypyrrole (PPy), and PEDOT also serve as promising alternatives due to their tunable electrical and thermal properties. Electrolytes act as the ion transport medium, with aqueous solutions like lithium chloride (LiCl), sodium sulfate ( $Na_2SO_4$ ), and potassium hydroxide (KOH) offering high ionic conductivity and environmental safety. Ionic liquids, including imidazolium- and phosphonium-based compounds, provide excellent electrochemical stability, while polymer gel and solid-state electrolytes, such as PVA- $H_3PO_4$  and PEO-based systems, enable flexibility in wearable applications. Separators are essential to prevent short circuits

while maintaining ion flow, with commonly used materials including polymer membranes like polyethylene (PE), polypropylene (PP), and polyvinylidene fluoride (PVDF), as well as nanoporous materials such as electrospun nanofibers and porous ceramic membranes. For wearable cooling devices, materials must be flexible, lightweight, biocompatible, and mechanically stable. Carbon-based electrodes, polymer gel electrolytes, and reinforced separators are particularly suitable for integration into textiles and flexible systems.

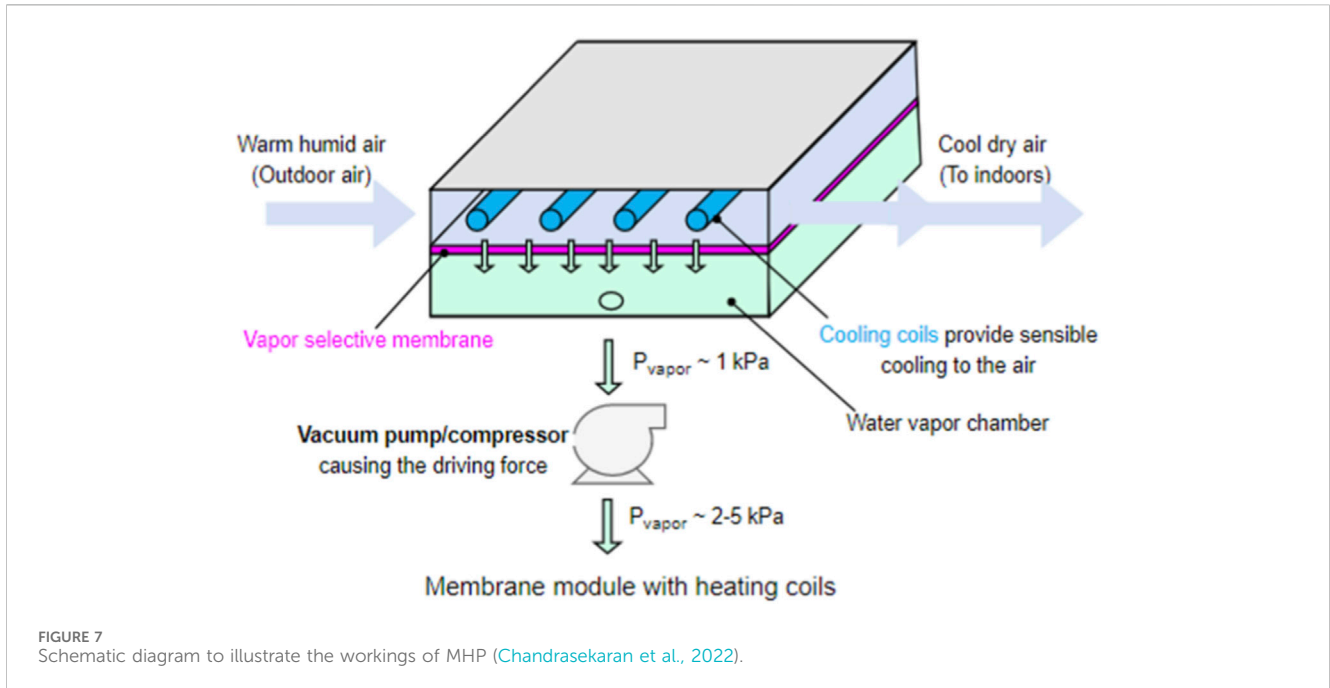
Unlike thermoelectric coolers, which require significant electrical input to generate a temperature gradient, electrochemical cooling can achieve comparable effects with lower power consumption (McKay et al., 2019). This makes it suitable for battery-powered or energy-harvesting systems, reducing dependency on large external power sources. Additionally, electrochemical cooling devices can be designed using lightweight and flexible materials, enhancing comfort and wearability without compromising performance. Thus, electrochemical cooling can be regarded as one of the sustainable solutions for heat stress mitigation in various real-world applications.

Despite its potential, several challenges must be addressed to enable the widespread adoption of electrochemical cooling in wearables. The longevity of electrochemical cooling systems is a critical concern, as repeated redox cycling may lead to electrode degradation and electrolyte instability. Additionally, ensuring skin safety and the biocompatibility of materials is essential for direct-contact applications. Research efforts are currently focused on developing novel electrolytes with high ionic conductivity and low volatility, as well as electrode materials with enhanced durability and thermal responsiveness.

### 3.2.5 Thermionic cooling

Thermionic solid-state cooling is an emerging cooling technology that utilizes thermionic emission to transport heat across a potential barrier. Electrons are thermally excited and emitted from a hot cathode, traverse a vacuum or semiconductor gap, and are collected at a cooler anode, thereby transferring heat and enabling efficient thermal management (Lee et al., 2000; Huffman, 2003). Thermionic coolers can function without moving parts, leading to increased reliability and reduced maintenance. Additionally, high-efficiency thermionic coolers can be achieved by reducing parasitic heat conduction.

Thermionic cooling relies on carefully selected materials for efficient electron emissions and heat transport. Common cathode materials include cesium-coated tungsten (Cs-W), which lowers the work function for enhanced emission, and lanthanum hexaboride ( $LaB_6$ ), known for its low work function ( $\sim 2.7$  eV) and high thermal stability. Barium strontium oxide (Ba-Sr-O) is widely used in dispenser cathodes, while graphene and other 2D materials emerge as promising alternatives due to their ultra-low work functions and superior electron mobility. For the anode, materials such as molybdenum (Mo), graphene, and silicon carbide (SiC) are commonly used to efficiently collect emitted electrons while maintaining high thermal and electrical conductivity. The interlayer or gap between the cathode and anode can be a vacuum, ensuring free electron transport, or a semiconductor such as gallium nitride (GaN) or silicon carbide



(SiC) to mitigate space-charge effects. Additionally, work function reduction coatings, including alkali metals like cesium and rubidium, as well as oxides such as BaO, SrO, and CaO, are applied to further enhance electron emission (Bellucci et al., 2021). Recent advancements in nanostructured materials, heterostructures, and composite materials aim to optimize thermionic cooling efficiency at lower operating temperatures, making the technology more viable for practical applications.

### 3.3 Membrane heat pumps

Membrane heat pump (MHP) works by simultaneously providing cooling and dehumidification through the transfer of moisture across a membrane, thereby avoiding the large penalty associated with condensing water vapor in traditional VC cycles (Lim et al., 2020; Oh et al., 2025). It was identified in 2014 by the U.S. Department of Energy as the top three promising technologies to achieve high energy savings (Goetzler et al., 2014). A schematic diagram is shown in Figure 7 to illustrate how MHP works (Chandrasekaran et al., 2022). A vacuum pump is used to create low vapor pressure to push incoming humid air into a water vapor-selective membrane in an isothermal process. The dry air is then passed through a heat exchanger to remove sensible heat, reducing the temperature of the dry air to the desired temperature before entering the conditioned space. The separated water vapor can then be rejected to the ambient air through another selective membrane. As can be seen, MHP offers the advantage of requiring only water, thereby reducing its environmental impact.

Since its introduction in 2000 (El-Dessouky et al., 2000), there have been many developments and design variations of MHP. The simplest single-module MHP uses only a membrane module and a vacuum pump. However, the performance is limited, with a COP range of up to about two reported due to inefficiencies related to the

vacuum pump (Oh et al., 2025). A dual-module MHP uses two membranes, typically known as dehumidification and rejection modules (DM and RM). A water vapor compressor is required to create a vacuum pressure at the DM permeate side and pressurize the rejected water vapor to reject it through the RM. The addition of RM significantly reduces the mass flow rate and pressure ratio of the vacuum pump (Bukshaisha and Fronk, 2019). Ahmad et al. simulated the dual-module MHP and concluded that MHP can achieve higher COP for varying ambient temperature ranges (Bukshaisha and Fronk, 2019). Lim et al. (2020) simulated two types of dual-module MHP systems: water vapor discharge and condenser combined type. It was found that the water vapor discharge MHP system offers a higher COP in general. Fix et al. developed a benchtop prototype of a dual-module MHP and, with the help of a thermodynamic model, concluded that MHP has the potential to reach a COP between 10 and 40 (Fix et al., 2024).

While some prototypes and patents have emerged for MHP (CLARIDGE and CULP, 2012; Cheon et al., 2022; Fix et al., 2024), for widespread use, some challenges still exist. Fix et al. found that the complete water vapor rejection through the membrane is vital for technology to maintain its advantage over others, as just a 10% decrease in water vapor rejection will result in a drop of COP below 3 (Fix et al., 2024). Other challenges that need to be resolved include the efficiency of the vacuum pump and membrane fouling (Bukshaisha and Fronk, 2019).

### 3.4 Radiant cooling systems

Radiant cooling systems are an alternative type of space cooling technology that makes use of a temperature-controlled radiant surface to exchange heat with occupants to augment thermal comfort (Hassan and Abdelaziz, 2020). Unlike other space cooling solutions, which typically rely on cooling air within a

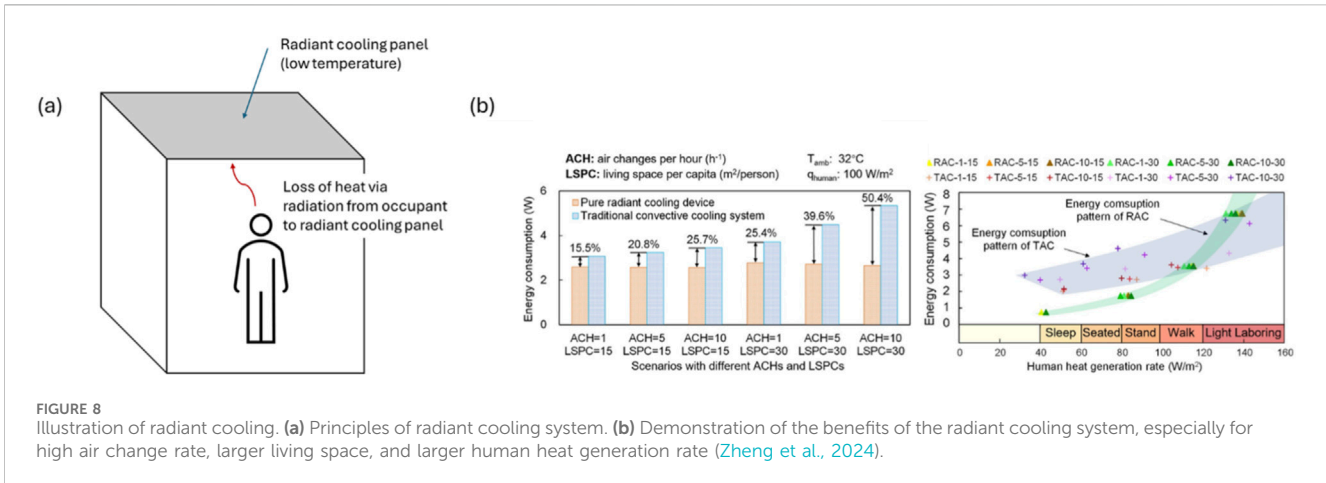


FIGURE 8 Illustration of radiant cooling. (a) Principles of radiant cooling system. (b) Demonstration of the benefits of the radiant cooling system, especially for high air change rate, larger living space, and larger human heat generation rate (Zheng et al., 2024).

space through convection, radiant cooling systems aim to supply cooling energy directly to occupants through predominantly radiant heat transfer (Zheng et al., 2024). An illustration of how a typical radiant cooling system works is depicted in Figure 8a. Since heat transfer occurs through radiation from the chilled cooling panel to the human’s skin, this effectively eliminates the need for air handling. Zheng et al. demonstrated the benefits of radiant cooling via a thermoelectric cooler and polyethylene films, showing that they can achieve a radiant cooling energy density of  $220 \text{ W/m}^2$ , potentially achieving an energy saving ratio of up to 50.4% (Zheng et al., 2024). Their experiment proves that a radiant cooling device offers the most benefit when compared to a traditional convective cooling system when the air change rate and living space increase, or when the human heat generation rate increases, as shown in Figure 8b. Globally, radiant cooling systems have also been implemented, such as in the Pearl River Tower in Guangzhou and the Diamond Building in Kuala Lumpur (Özbeý and Turhan, 2022). To advance technology towards widespread implementation, the major challenge of condensation and efficiency needs to be resolved. Radiant cooling system relies on a large area low temperature surface and achieves its maximum efficiency if condensation and convection are limited.

Teitelbaum et al. also introduced a membrane-assisted radiant cooling system in 2020, which uses a membrane system to prevent unwanted air cooling and condensation (Teitelbaum et al., 2020). The use of a thermally transparent membrane effectively overcomes this challenge. The radiant cooling system demonstrated no condensation with a chilled water supply temperature of  $12.7 \text{ }^\circ\text{C}$  below the dew point. Tang et al. also propose in 2024 an anti-condensation radiant cooling unit that makes use of an infrared-transparent silicon wafer that separates the cooling radiant panel from human air (Tang et al., 2024). The use of the anti-condensation layer effectively increases the performance of the radiant cooling system by 60%. However, even with the anti-condensation measures, condensation remains a major issue in high-temperature and high-humidity environments. Hence, to continue to advance radiant cooling systems, there is a need to combine different anti-condensation and dehumidification strategies while still maintaining energy savings.

### 3.5 District cooling

The increasing need for energy-efficient and environmentally friendly cooling technologies has driven the exploration of district cooling systems, which offer significant energy savings and reduced GHG emissions compared to conventional cooling methods. Approximately 17% of global electricity consumption is attributed to refrigeration applications, contributing to nearly 8% of total GHG emissions (Al-Nini et al., 2023). District cooling (DCS), which centralizes cooling production and distribution, has shown promise in reducing energy consumption and environmental impact. Compared to traditional cooling systems, DCS achieves higher efficiency due to large-scale industrial chillers, which generally outperform smaller, decentralized units. The initial capital and operational costs are minimized by eliminating the need for separate cooling units in each building. Additionally, the load distribution across multiple buildings results in a more uniform demand profile, preventing excessive peak loads and optimizing energy use (Katcher et al., 2025). Another benefit of DCSs is that they have lower GHG emissions, contributing to climate change mitigation efforts.

#### 3.5.1 District cooling in hot climates and urban areas

Countries with hot climates, particularly those near the tropics, face significant challenges related to high cooling demands. The Gulf Cooperation Council (GCC) region, which includes Saudi Arabia, Kuwait, Bahrain, Oman, Qatar, and the United Arab Emirates, experiences extreme heat conditions, leading to high electricity consumption. In the GCC, air conditioning accounts for approximately 70% of household electricity consumption in Saudi Arabia, 60% in Oman, and 36% in the United Arab Emirates. The region’s cooling demand is expected to triple by 2030 compared to 2010 levels (Al-Nini et al., 2023).

Urban areas with high population densities benefit significantly from DCS due to their energy-intensive environments. The implementation of centralized cooling plants helps mitigate peak electricity demand during heat waves, reducing strain on the power grid. According to the International Energy Agency (IEA), space cooling accounts for 20% of building electricity consumption, responsible for approximately 1 Gton of  $\text{CO}_2$  emissions annually.

By 2050, the cooling demand could increase by 100%, with two-thirds of households worldwide equipped with air conditioning systems (Neri et al., 2024).

### 3.5.2 Integration of renewable energy and advanced technologies

Enhancing DCS efficiency requires integration with renewable energy sources, such as solar or geothermal energy, along with thermal energy storage (TES) systems. TES tanks, combined with chillers, enable better load management, reducing peak electricity demand. Free cooling sources, such as cold-water basins or waste heat from industrial processes, can also be incorporated to improve energy savings. Fifth-generation district heating and cooling (5GDHC) is an emerging approach that promotes heat sharing among prosumers through a bidirectional, low-temperature network (Gjoka et al., 2025). This system reduces reliance on fossil fuels by enabling energy exchange among buildings with complementary heating and cooling needs. Decentralized heat pumps are employed to bridge temperature gaps, reducing operational costs and improving efficiency. Studies suggest that 5GDHC systems can achieve electricity savings of up to 40% compared to conventional setups (Chaudhry et al., 2024; Qin and Gosselin, 2024).

### 3.5.3 Snow cooling and seasonal thermal storage

An alternative district cooling approach involves using natural sources such as winter snow. Seasonal snow storage systems have been implemented in countries like Sweden, Norway, and Japan, where snow is collected and stored in insulated tanks for use during warmer months. This method offers significant energy savings, as melting snow provides a free cooling source with high latent heat of fusion. Additionally, integrating snow cooling with solar photovoltaic (PV) electricity can further reduce the carbon footprint of such systems (Sreenath et al., 2024).

Phase change materials (PCM) also offer a viable option for seasonal thermal energy storage. PCMs store thermal energy in the form of latent heat, allowing for effective load shifting. However, selecting appropriate PCM parameters, such as melting temperature and storage size, is crucial to optimizing performance. Recent studies highlight that PCM-based storage, when coupled with photovoltaic integration, can enhance CO<sub>2</sub> emission reduction efforts (Yang et al., 2024).

### 3.5.4 Evolution and future research directions of district cooling systems

District cooling technology has evolved through multiple generations.

- 1. First Generation:** Pipeline refrigeration systems utilizing decentralized evaporators and centralized condensers.
- 2. Second Generation:** Adoption of large compression chillers using cold water as a distribution fluid.
- 3. Third Generation:** Integration of diverse cooling sources, including absorption chillers and natural cooling from lakes and streams.
- 4. Fourth Generation:** Focus on energy decarbonization, integrating renewable energy and combined heating-cooling synergy.

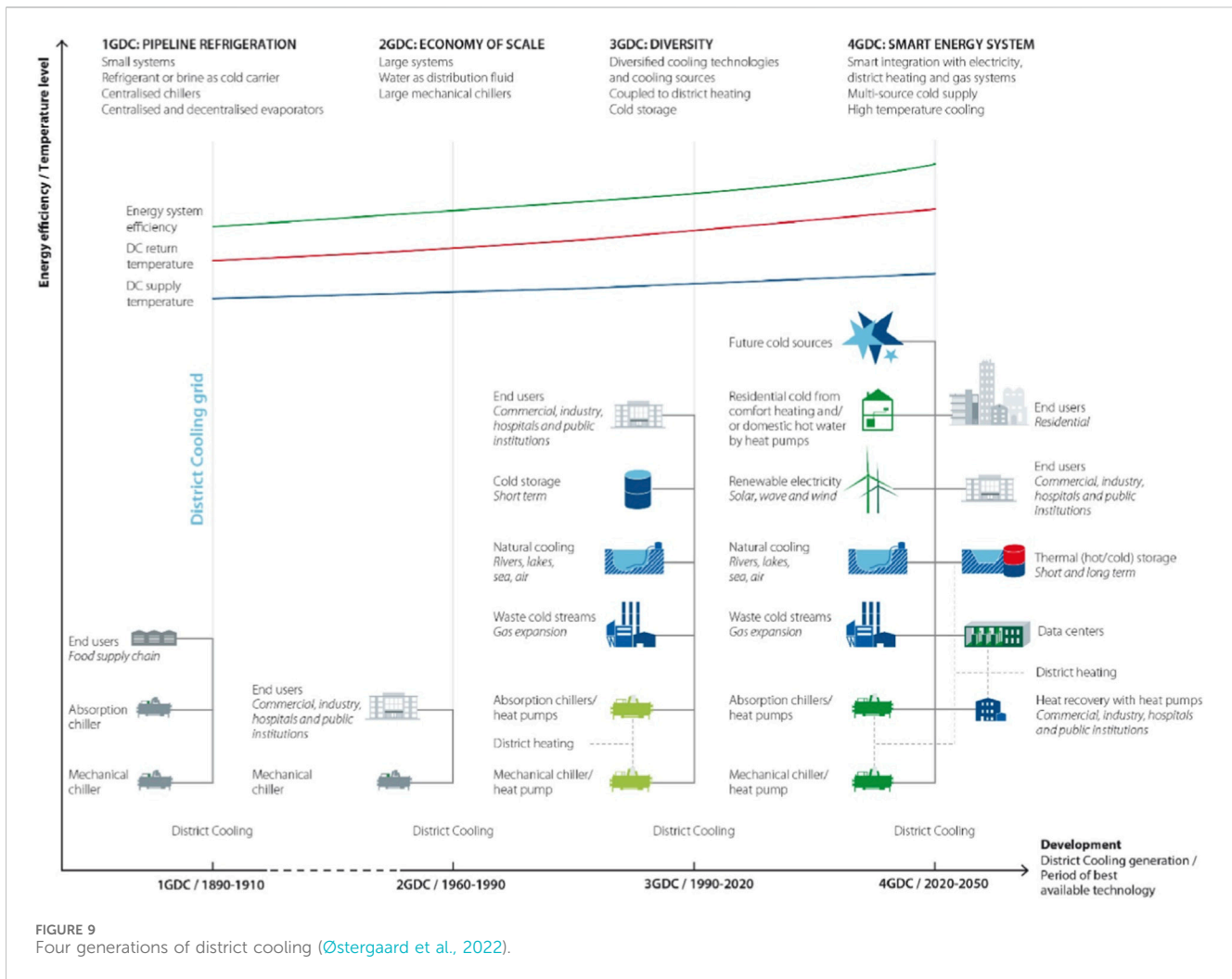
- 5. Fifth Generation (Present):** Transition to bidirectional, low-temperature networks with decentralized electrified heat pumps and enhanced cross-sectoral integration (Alotaibi and Alhuyi Nazari, 2023; Yao et al., 2024). Figure 9 shows four generations of district cooling technology.

Future research directions in district cooling focus on enhancing energy efficiency, integrating renewable energy sources, and optimizing system design through advanced modeling and control strategies. Adopting low-carbon and waste heat utilization technologies, such as absorption and adsorption, is gaining traction to reduce reliance on conventional electricity-driven cooling. Thermal energy storage (TES) systems, including phase change materials (PCMs) and chilled water storage, are being explored to improve load flexibility and peak demand management. Integrating artificial intelligence (AI) and digital twins enables real-time monitoring, predictive maintenance, and dynamic optimization of district cooling networks. Additionally, the development of next-generation cooling fluids and high-efficiency heat exchangers aims to minimize environmental impact and improve performance. Future research also emphasizes smart grid integration and district-wide energy sharing, enabling interconnected cooling systems to enhance sustainability and resilience in urban environments.

## 3.6 Other cooling technologies for the built environment

Dense urban areas experience intensified Urban Heat Island (UHI) effects (Mughal et al., 2020; Li and Liu, 2021), especially in urban areas, where temperatures are higher than in surrounding rural areas. This is driven by extensive land use changes, high-rise buildings, paved surfaces, and reduced vegetation, all contributing to heat retention and limited natural cooling (Vujovic et al., 2021). In Southeast Asia, the number of very warm days is rising due to residential expansion (MSS, 2022). As urbanization grows, especially in developing countries, impervious surfaces expand, further intensifying UHI effects. Pervious pavements, with their rougher surfaces, can have lower solar reflectance and thermal conductivity, exacerbating heat buildup (Li et al., 2013). Therefore, there is an urgent need for technologies to address UHI and improve thermal comfort in dense urban environments.

There has been an initiative to address this through painting techniques, such as cool roofs. Cool roofs are passive cooling systems (Berdahl and Bretz, 1997), whose surface is exposed to solar radiation, but it has a high solar reflectance and high thermal emittance (Revel et al., 2014). Cool roofing products are made of highly reflective and emissive materials that can remain approximately 28 °C–33 °C cooler than traditional materials during peak summer weather. Building owners and roofing contractors have used these types of cool roofing products for more than 20 years in developed countries. Traditional roofs in the United States, in contrast, can reach summer peak temperatures of 66 °C–85 °C, thus creating a series of hot surfaces as well as warmer air temperatures nearby. In Singapore, several mitigation measures have been practiced. Donthu et al. (2024) reported that the Cool Canyon had up to 30% reduction in sensible heat release from

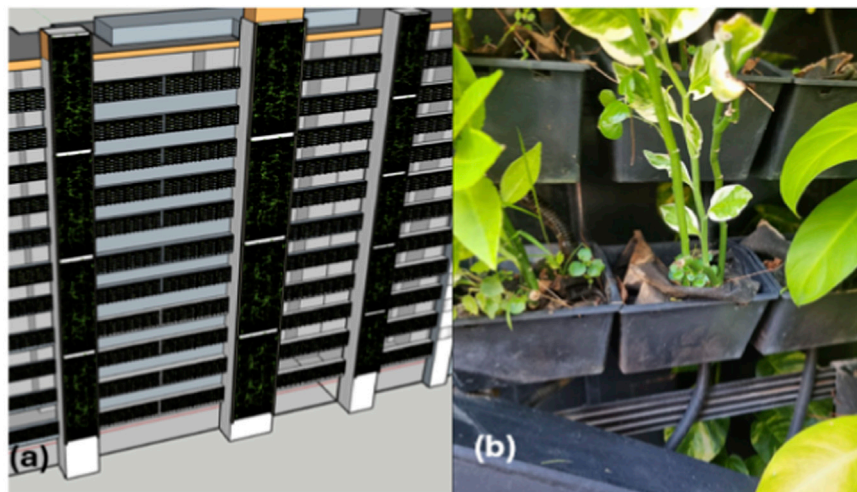


the built-up surfaces, which resulted in the air temperature in Cool Canyon being cooler than that in the Conventional Canyon by up to 2 °C around late afternoon.

Another strategy to mitigate the urban heat island effect is the incorporation of green building practices, such as green roofs and walls. These vegetated surfaces help reduce temperatures by providing shade, enhancing aesthetics, and regulating building temperature through photosynthesis and evapotranspiration. Green walls, both indoors and outdoors, act as thermal buffers by absorbing heat during the day and releasing it at night (Wong et al., 2021). Plants also cool the air and surfaces through evapotranspiration, creating a cooler microclimate and reducing the overall urban heat island effect. Additionally, plants have a higher albedo than urban materials like asphalt, reflecting more solar radiation and reducing heat absorption. This leads to less need for cooling systems, reducing greenhouse gas emissions. William et al. (2022) modelled the integration of modular vertical farms into urban residential areas in Singapore (William et al., 2022). Their design considers cloud shading, sunpath, and air velocity, demonstrating potential for green walls on building facades, rooftops, or multi-storey car parks, as illustrated in Figure 10.

Green infrastructure cools urban environments through mechanisms such as evapotranspiration of greenery, provision of shade, and increased albedo. These combined effects reduce the thermal load on the built environment and its inhabitants. Heat flux interception by the plant canopy, which provides shade, is one of the most effective cooling methods, with plants intercepting 70%–90% of incoming solar radiation. This reduction in both shortwave and longwave radiation helps cool urban surfaces like buildings, roads, and pavements. Green infrastructure can also lower energy requirements for cooling, reducing anthropogenic heat sources and leading to potential energy savings of 20%–80%. Homeowners spend less energy to cool their rooms as vertical farms block direct sunlight.

Studies show that light conversion films, applied to the sides of buildings, can mitigate heat entering existing structures by converting long-wavelength infrared heat waves into visible light. Using temperature and humidity sensors, we can measure the microclimate created by the light conversion film and assess its effectiveness. The reduced temperature and enhanced infrared conversion contribute to a 20%–30% increase in leafy green yield (Wei Ang et al., 2024). Goh et al. (2025) reported using BIM Revit to model the growth of vegetation on building facades and its impact



**FIGURE 10**  
(a) Corridors with walkways for each residential units and green vertical façade—left, (b) individual planter unit installed as green wall for facades.

on solar radiation reduction (Goh et al., 2025). Such modeling tools allow urban planners to test the effectiveness of cooling solutions before implementing them in the built environment.

## 4 Conclusion

The global overreliance on traditional air-conditioning systems has substantially contributed to greenhouse gas emissions and intensified the Urban Heat Island (UHI) effect, thereby accelerating global temperature rise. This underscores the urgent necessity to develop sustainable cooling technologies capable of delivering thermal comfort while minimizing environmental impact.

This review emphasizes the growing importance of innovative human cooling solutions as viable alternatives to conventional vapor-compression systems. Two main areas were discussed: localized cooling using Personal Cooling Devices (PCDs) and large-scale sustainable space cooling technologies.

Personal Cooling Devices (PCDs) represent a promising approach for energy-efficient and targeted thermal management. Through passive, active, or hybrid cooling mechanisms—such as cooling textiles, thermoelectric garments, and liquid cooling systems—PCDs can effectively lower local skin temperature and improve comfort. Despite these advantages, current commercial devices face persistent challenges related to cooling efficiency, durability, weight, and user comfort. Further optimization is needed to enhance their thermal performance and practicality for everyday or occupational use.

The review also highlights the assessment of thermal comfort in localized cooling, a relatively underexplored area. Since localized cooling differs fundamentally from whole-space air conditioning, its influence on human perception, physiological responses, and long-term adaptability remains inadequately understood. Addressing these knowledge gaps is essential for broader acceptance and successful deployment of PCDs in real-world scenarios.

Beyond personal cooling, sustainable space cooling solutions such as solid-state cooling technologies (e.g., thermoelectric, electrocaloric, and magnetocaloric systems), membrane-based heat pumps, and radiant cooling systems have shown significant potential. These emerging technologies can outperform traditional vapor-compression systems in both energy efficiency and environmental sustainability. Furthermore, integrating renewable energy sources, phase change materials, and smart control systems can significantly enhance the performance and carbon footprint of future cooling systems. Complementary innovations such as district cooling networks, radiative cooling materials, and cooling paints further contribute to reducing dependence on conventional systems and promoting urban decarbonization.

Taken together, the findings of this review extend existing work on both personal and space cooling technologies by situating them within a unified “human cooling” framework. While previous studies have examined these approaches largely in isolation, our synthesis highlights their complementary roles: localized cooling can substantially reduce energy demand and improve individual thermal comfort, yet remains insufficient as a standalone replacement for space cooling, while emerging large-scale solutions offer system-level efficiency but face scalability and cost constraints. Importantly, this integrated perspective has direct implications for practice and policy. For engineers and building designers, it suggests that hybrid strategies combining localized and space-based cooling can deliver meaningful energy savings without compromising comfort. For manufacturers, it underscores the need to prioritise durability, flexibility, and heat rejection in next-generation wearable systems. From a policy standpoint, the results support the development of standards tailored to localized cooling, the inclusion of alternative cooling technologies in energy codes, and targeted incentives for district-scale and low-carbon cooling infrastructure. Together, these measures can help translate technological advances into deployable solutions for mitigating heat stress while reducing the environmental footprint of cooling.

## 4.1 Limitations and future research directions

This study has several limitations that should be considered when interpreting the findings. First, although this review draws on a broad range of published literature, the selection and synthesis of studies may be subject to publication and disciplinary bias, as emerging technologies with limited validation are often underreported in large-scale comparative datasets. Second, the market and user survey conducted to evaluate commercial personal cooling devices was based on a moderate sample size and specific products, which may not fully represent the diversity of user populations, occupational contexts, or climatic conditions globally. As such, user perceptions of comfort, usability, and performance may vary across regions, activities, and cultural expectations. Finally, while this review identifies general technological trends and performance trade-offs, the generalizability of specific quantitative outcomes is constrained by differences in experimental protocols, testing environments, and device configurations across studies. Future work should therefore include larger, cross-climatic field trials, standardized evaluation metrics, and longitudinal assessments to strengthen the external validity and policy relevance of human cooling technologies.

Beyond data-related constraints, this study is subject to both methodological and conceptual limitations. Methodologically, this review synthesizes findings from studies that employ heterogeneous experimental setups, performance metrics, and evaluation environments, which limits the comparability of quantitative outcomes across technologies. The user survey further reflects short-term evaluations of a limited set of commercial devices rather than long-duration or field-based deployment. Conceptually, the proposed “human cooling” framework emphasizes technological performance, energy efficiency, and thermal comfort, and therefore does not fully account for broader socio-economic factors such as cost accessibility, behavioral adaptation, infrastructure readiness, or regulatory barriers that may shape real-world adoption. Consequently, the findings should be interpreted as a technology-focused perspective rather than a comprehensive assessment of all determinants of cooling transitions. Future work integrating standardized testing, longitudinal field studies, and interdisciplinary analyses is needed to strengthen both methodological rigor and conceptual scope.

In addition, while recent progress in human cooling technologies is encouraging, several critical challenges remain unresolved. To accelerate innovation and practical deployment, future research should focus on the following key areas:

1. Material Stability and Durability
  - a. Enhance the long-term stability of advanced cooling materials, such as electrocaloric and magnetocaloric compounds, under cyclic thermal and mechanical stresses.
  - b. Develop lightweight, flexible, and breathable materials for wearable cooling applications.
2. Energy Efficiency and Power Management
  - a. Improve the energy efficiency of active cooling systems through hybrid power architectures and adaptive control algorithms.
  - b. Extend battery life and explore self-powered wearable systems using energy harvesting technologies.
3. Thermal Comfort and Human Factors
  - a. Conduct systematic studies on how localized cooling influences thermal perception, comfort thresholds, and physiological responses.
  - b. Develop standardized testing protocols for evaluating user comfort and safety in PCDs.
4. Scalability and System Integration
  - a. Investigate the scalability of district cooling networks and membrane heat pumps for large-scale urban implementation.
  - b. Integrate renewable energy systems (e.g., solar, geothermal) with advanced cooling solutions for carbon-neutral operation.
5. Sustainability and Life-Cycle Assessment
  - a. Evaluate the environmental footprint and recyclability of new cooling technologies through comprehensive life-cycle analyses.
  - b. Develop circular design frameworks to minimize waste and resource use across manufacturing and deployment stages.

By addressing these research priorities, future developments can bridge the gap between laboratory-scale innovation and real-world application, paving the way toward climate-resilient and energy-efficient human cooling solutions.

## Author contributions

EA: Conceptualization, Data curation, Formal Analysis, Investigation, Visualization, Writing – original draft, Writing – review and editing. AY: Conceptualization, Data curation, Formal Analysis, Investigation, Visualization, Writing – original draft, Writing – review and editing. CS: Conceptualization, Visualization, Writing – original draft, Writing – review and editing. PW: Conceptualization, Funding acquisition, Supervision, Writing – original draft, Writing – review and editing.

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The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fther.2026.1602847/full#supplementary-material>

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